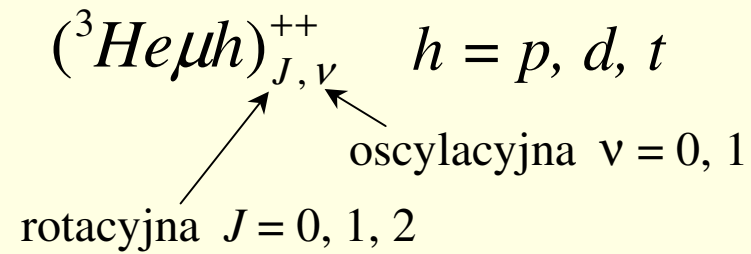
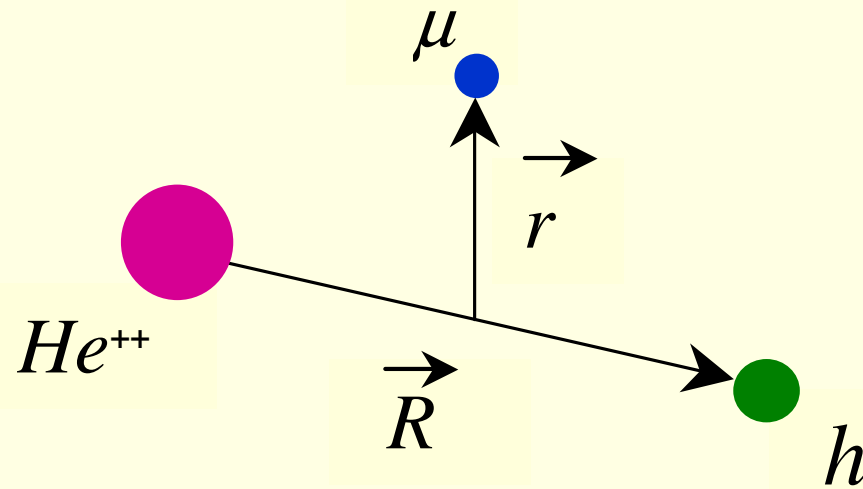


Rezonanse w deekscytacji molekuł mionowych i rozpraszanie elastyczne atomów mionowych helu

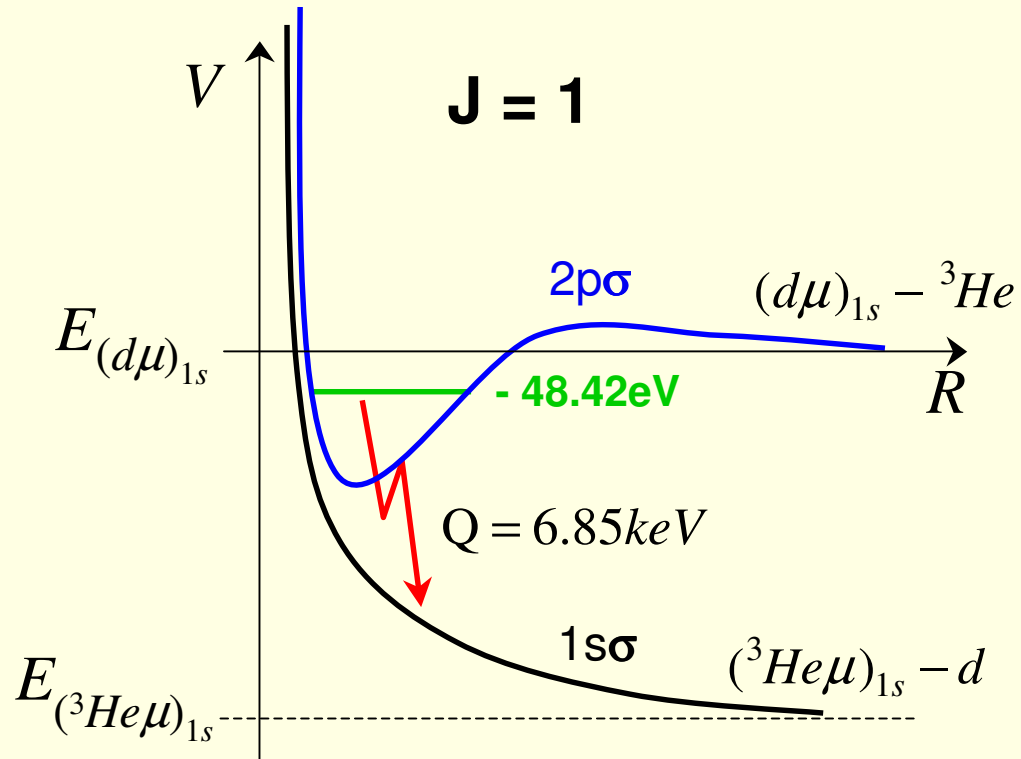
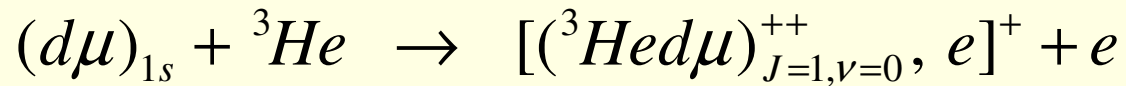
Wilhelm Czaplński

Katedra Zastosowań Fizyki Jądrowej

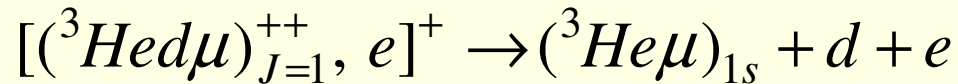
1. Rezonanse w deekscytacji molekuł mionowych



Powstawanie molekuly ($\lambda \sim 10^{-8} \text{ s}^{-1}$, LHD):

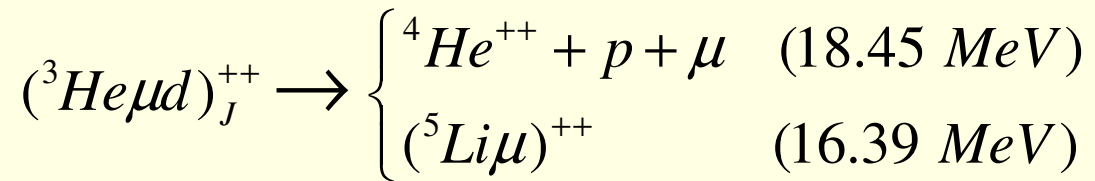


**Rozpad po czasie
 10^{-12} s**



Reakcje syntezy w molekułach mionowych

Z relacji nieoznaczoności $E_{\text{j\u0105der}} \sim 1\text{keV}$



Teoria: $\lambda_f^{J=0} = 1.9 \cdot 10^5 \text{ s}^{-1} \div 3.8 \cdot 10^6 \text{ s}^{-1}$

$$\lambda_f^{J=1} = 6.5 \cdot 10^2 \text{ s}^{-1}$$

$$\frac{\lambda_f^{J=0}}{\lambda_f^{J=1}} \approx 300 \div 6000$$

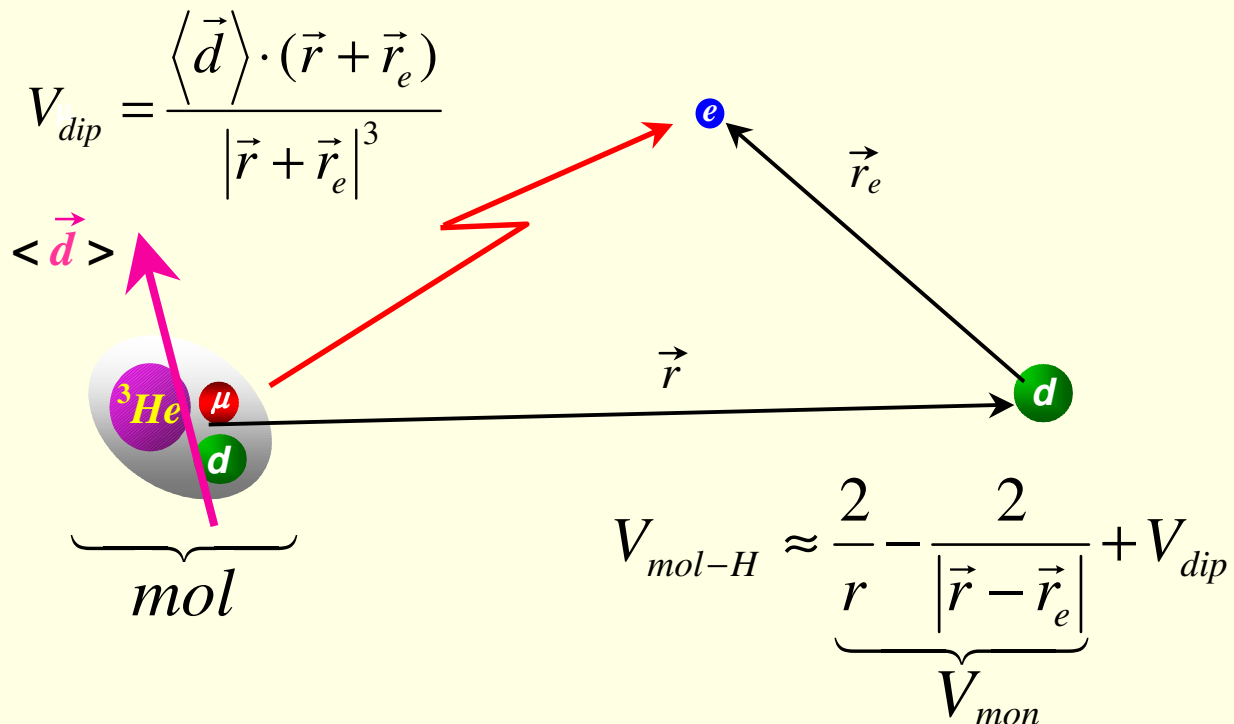
Eksperyment: $\lambda_f^{\text{exp}} = 4.5 \cdot 10^5 \div 6.9 \cdot 10^5 \text{ s}^{-1}$

$$\lambda_f^{\text{exp}} = \beta_0 \lambda_f^{J=0} + \beta_1 \lambda_f^{J=1} \quad \beta_0 + \beta_1 = 1$$

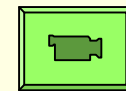
Molekuła powstaje w stanie $J = 1$
 synteza ze stanu $J = 0$

! Musi istnieć przejście $1 \rightarrow 0$!

Możliwy proces: $({}^3\text{He}\mu d)_{J=1}^{++} + D \rightarrow ({}^3\text{He}\mu h)_{J=0}^{++} + d + e$

$$V_{dip} = \frac{\langle \vec{d} \rangle \cdot (\vec{r} + \vec{r}_e)}{|\vec{r} + \vec{r}_e|^3}$$


$$V_{mol-H} \approx \underbrace{\frac{2}{r} - \frac{2}{|\vec{r} - \vec{r}_e|}}_{V_{mon}} + V_{dip}$$

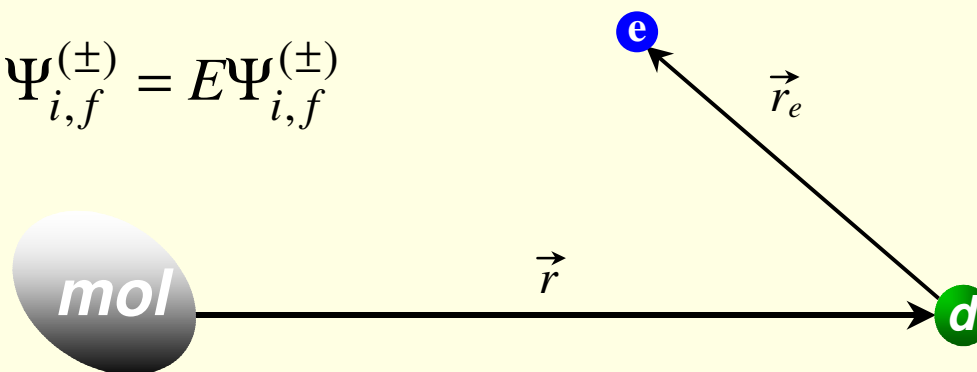


Rachunki w pełni kwantowe – metoda DWBA prawie analityczne

Złota reguła Fermiego

$$d\sigma_{10} = \frac{2\pi}{V_i} \frac{1}{2J_i + 1} \sum_{M_i = -1}^1 \left| \langle \Psi_f^- | V_{dip} | \Psi_i^+ \rangle \right|^2 \delta(E_i - E_f) \frac{d^3 k_f}{(2\pi)^3} \frac{d^3 k_e}{(2\pi)^3} \frac{d\Omega_{k_i}}{4\pi}$$

$$(\hat{T}_{rel} + \hat{H}_{mol} + V_{mon}) \Psi_{i,f}^{(\pm)} = E \Psi_{i,f}^{(\pm)}$$



$$\Psi_{i,f}^{(\pm)} = \Phi_{i,f}^{mol} \phi_{i,f}^e(r, \vec{r}_e) \phi_{\vec{k}_{i,f}}^{(\pm)rel}(\vec{r})$$

$$\phi_{\vec{k}_{i,f}}^{(\pm)rel}(\vec{r}) = \sum_{l_{i,f}=0}^{\infty} i^{l_{i,f}} (2l_{i,f} + 1) e^{\pm i\delta_{l_{i,f}}} \frac{\chi_{l_{i,f}}(r)}{kr} P_{l_{i,f}}(\hat{k}_{i,f} \cdot \hat{r})$$

$$V_{dip} = \frac{\langle \vec{d} \rangle \cdot (\vec{r} + \vec{r}_e)}{|\vec{r} + \vec{r}_e|^3} \quad \begin{array}{l} \text{rowinięcie} \\ \text{multipolowe} \end{array} = \sum_{L=2}^{\infty(4)} \dots \quad \text{!}$$

$$\sigma_{10} = \frac{2^8}{9} \pi \frac{d^2}{V_i k_i^2} \sum_{L=0}^{\infty(4)} \sum_{l_i l_f} (2l_i + 1)(2l_f + 1) \begin{pmatrix} l_i & l_i & L \\ 0 & 0 & 0 \end{pmatrix}^2 \times$$

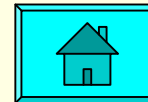
$$\times \int_0^{\infty} dk_f f_L^e(k_f) \underbrace{G_{l_i l_f L}^{rel}(k_i, k_f)}$$

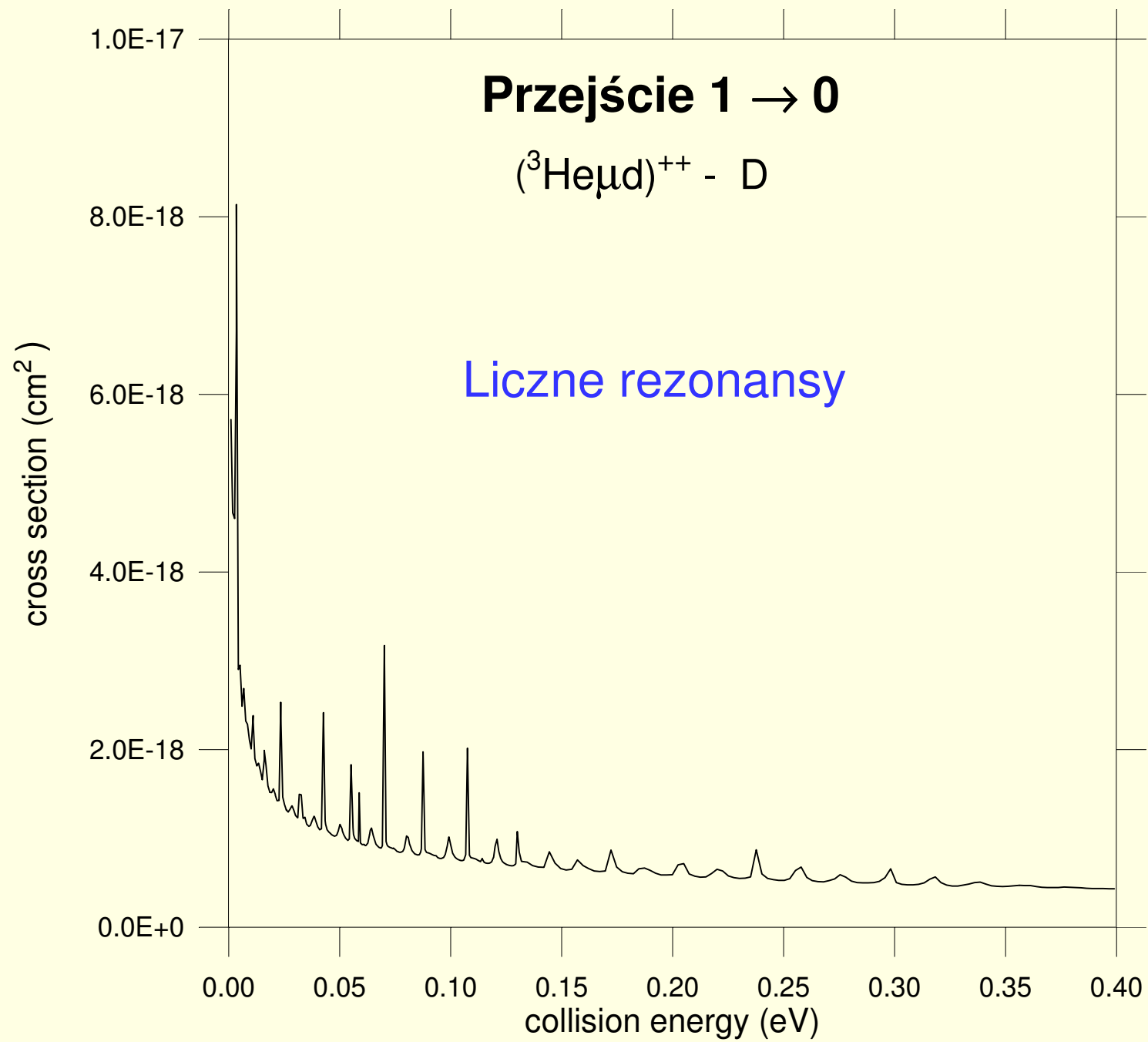
$$G_{l_i l_f L}^{rel}(k_i, k_f) = \int_0^{\infty} \frac{\chi_{l_i}(r) \chi_{l_f}(r)}{r^{L+1}} dr$$

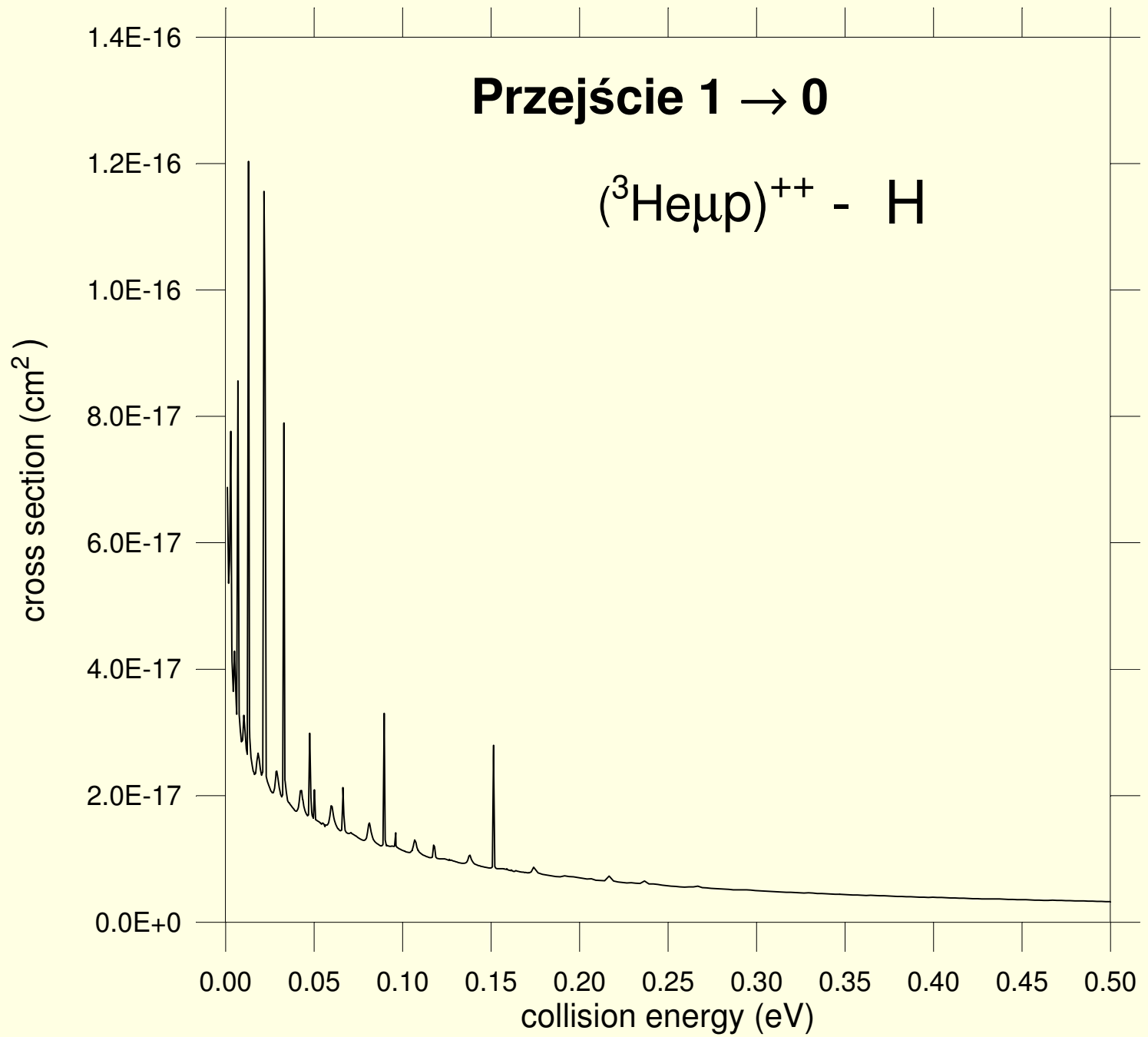
$$V_{dip} = \frac{d}{\sqrt{3}} \sum_{i=1}^3 a_{im_j} \sum_{L=2}^{\infty} W_L(\hat{r}, \hat{r}_e, \hat{e}_i) \frac{r_e^{L-1}}{r^{L+1}},$$

gdzie

$$W_L(\hat{r}, \hat{r}_e, \hat{e}_i) = (-1)^L \pi^{3/2} \frac{8}{\sqrt{3}} \sqrt{\frac{L}{2L+1}} \sum_{m_L=-L}^L \sum_{m_1, m_2} C_{L-1, m_1}^{L m_L} \bar{Y}_{L m_L}(\hat{R}) Y_{L-1 m_1}(\hat{\rho}) Y_{1 m_2}(\hat{e}_i)$$





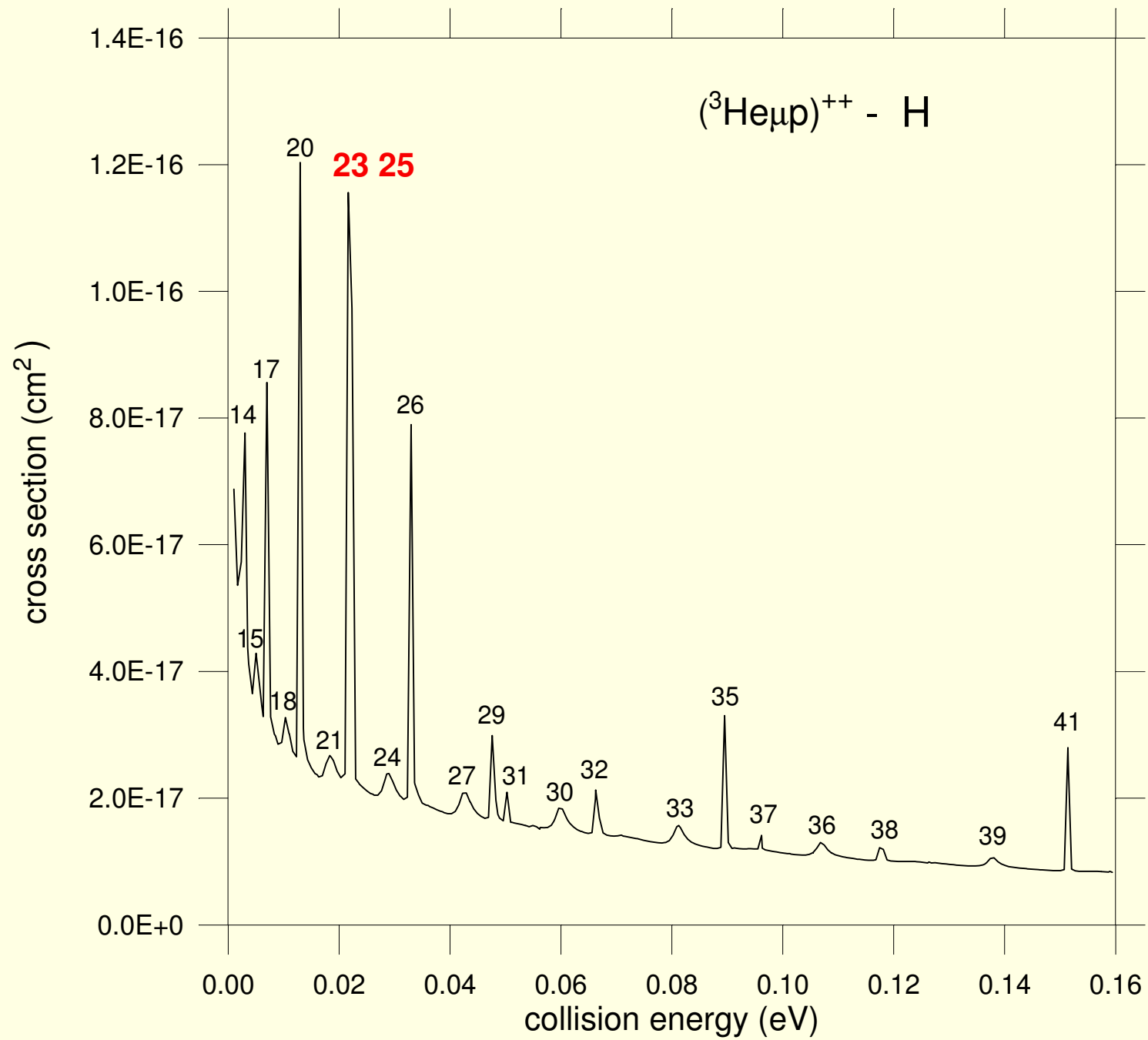


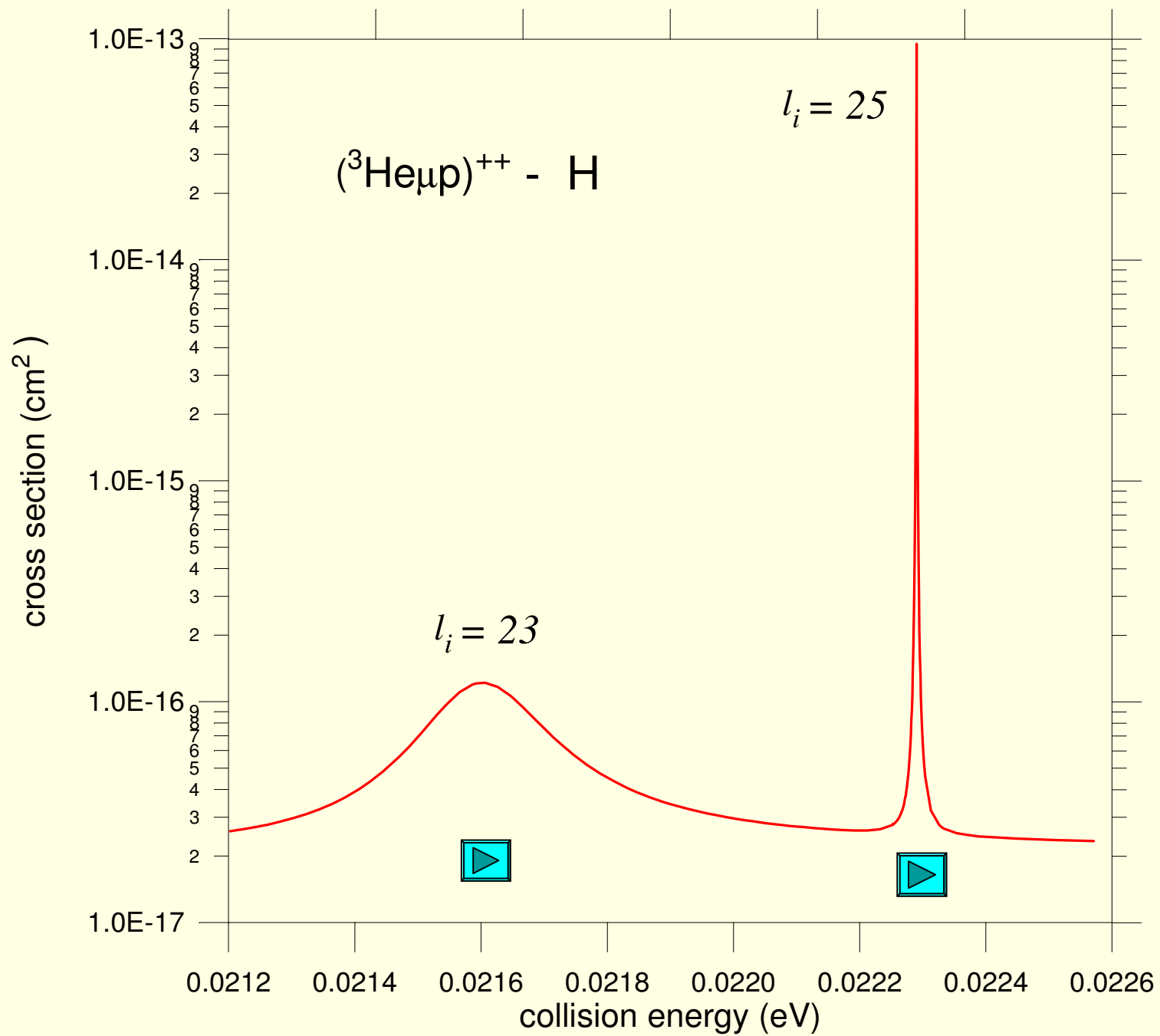
Jaka jest natura tych rezonansów ?

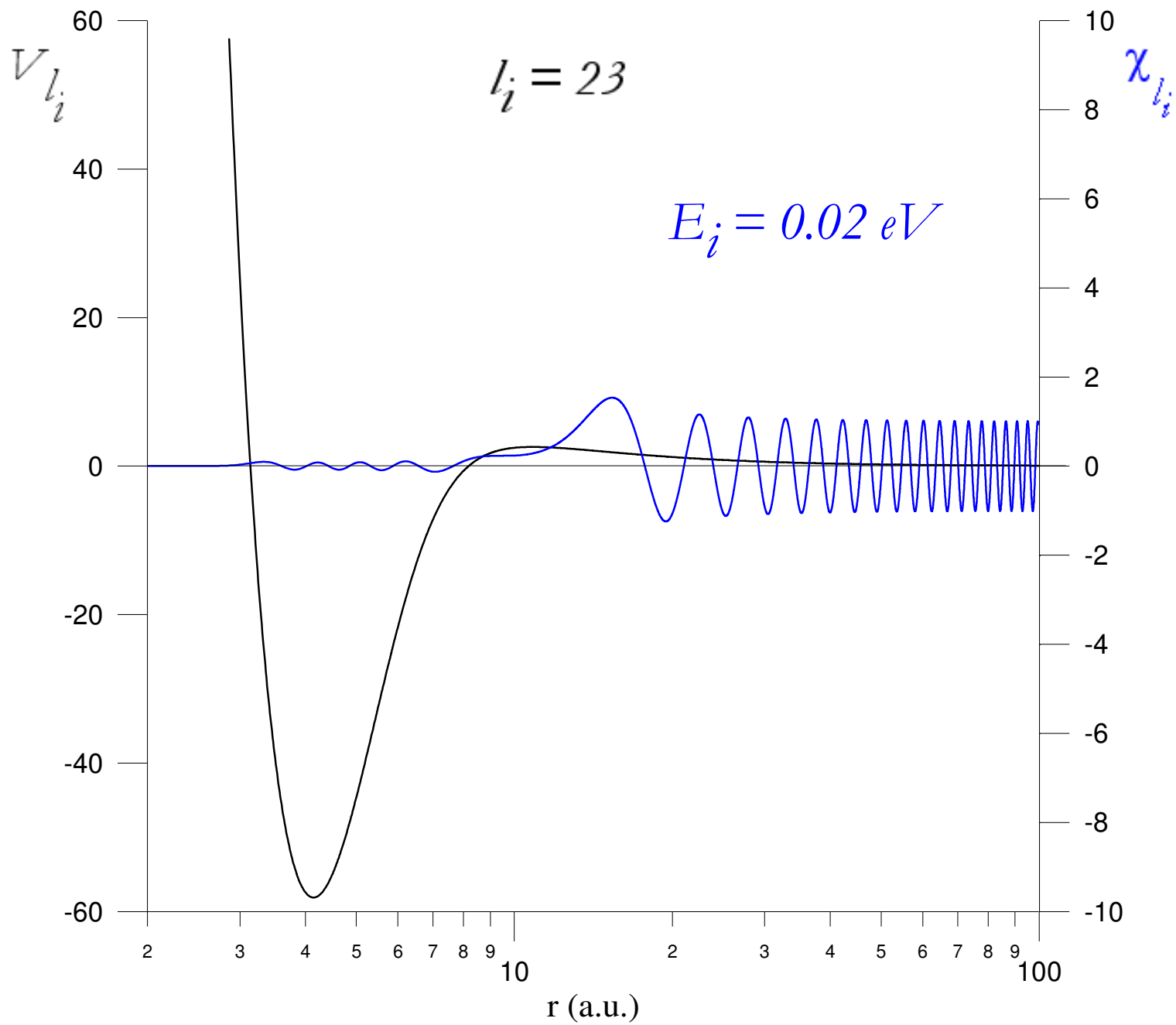
$$G_{l_i l_f L}^{rel}(k_i, k_f) = \int_0^{\infty} \frac{\chi_{l_i}(r) \chi_{l_f}(r)}{r^{L+1}} dr$$

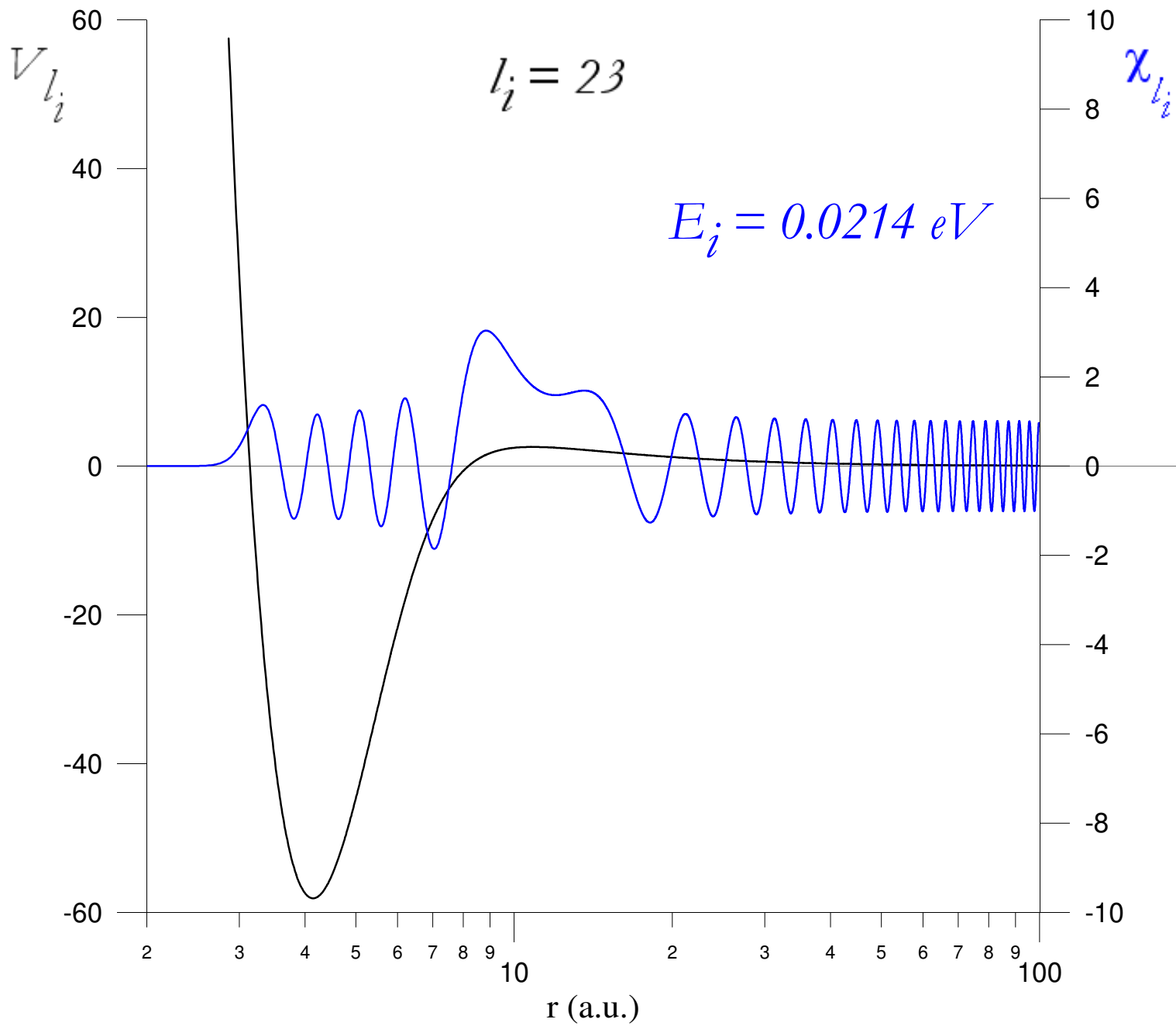
-przyjmuje bardzo duże wartości dla pewnych l_i

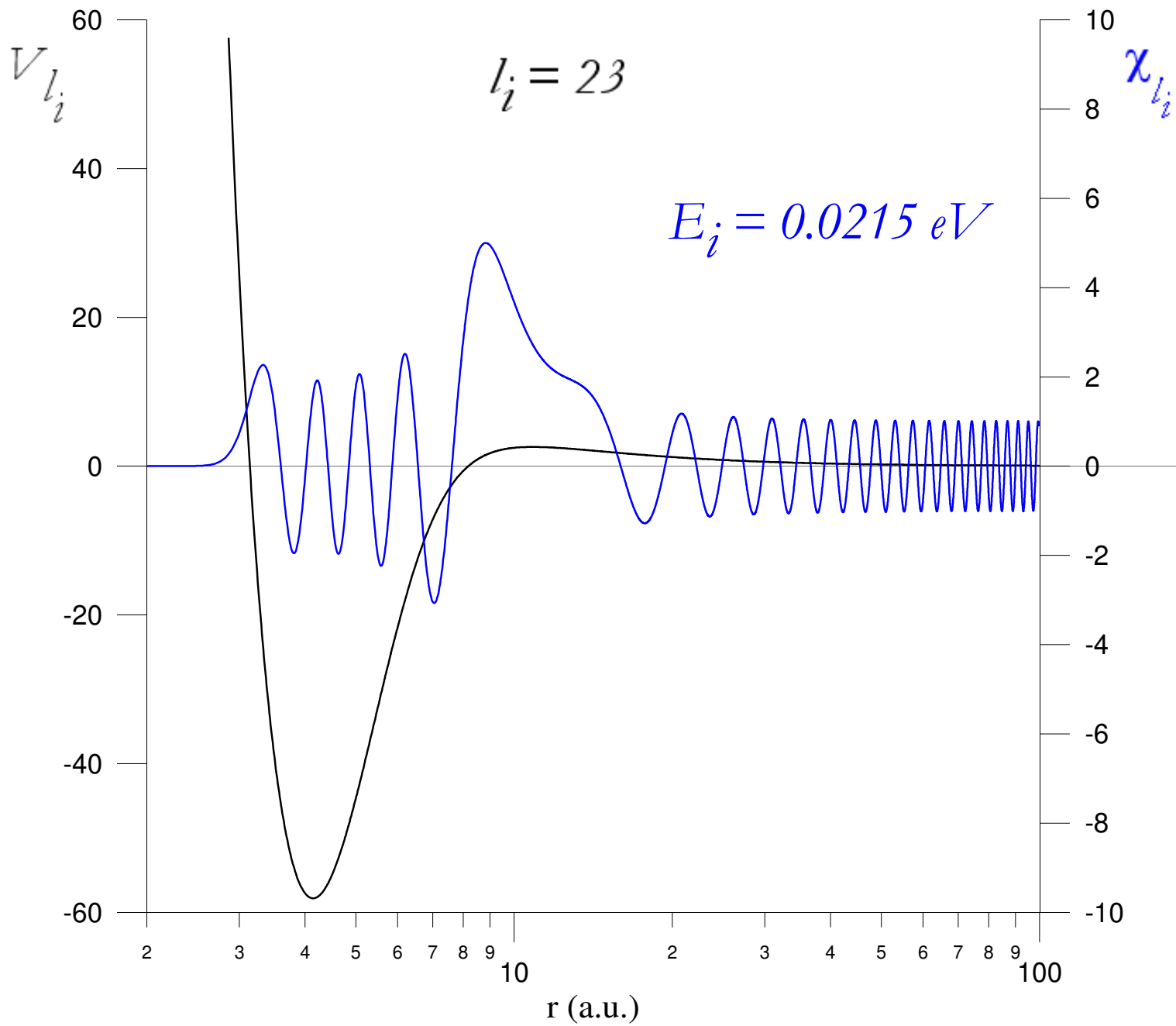
$\chi_{l_i}(r)$ - musi mieć bardzo dużą amplitudę w obszarze działania potencjału

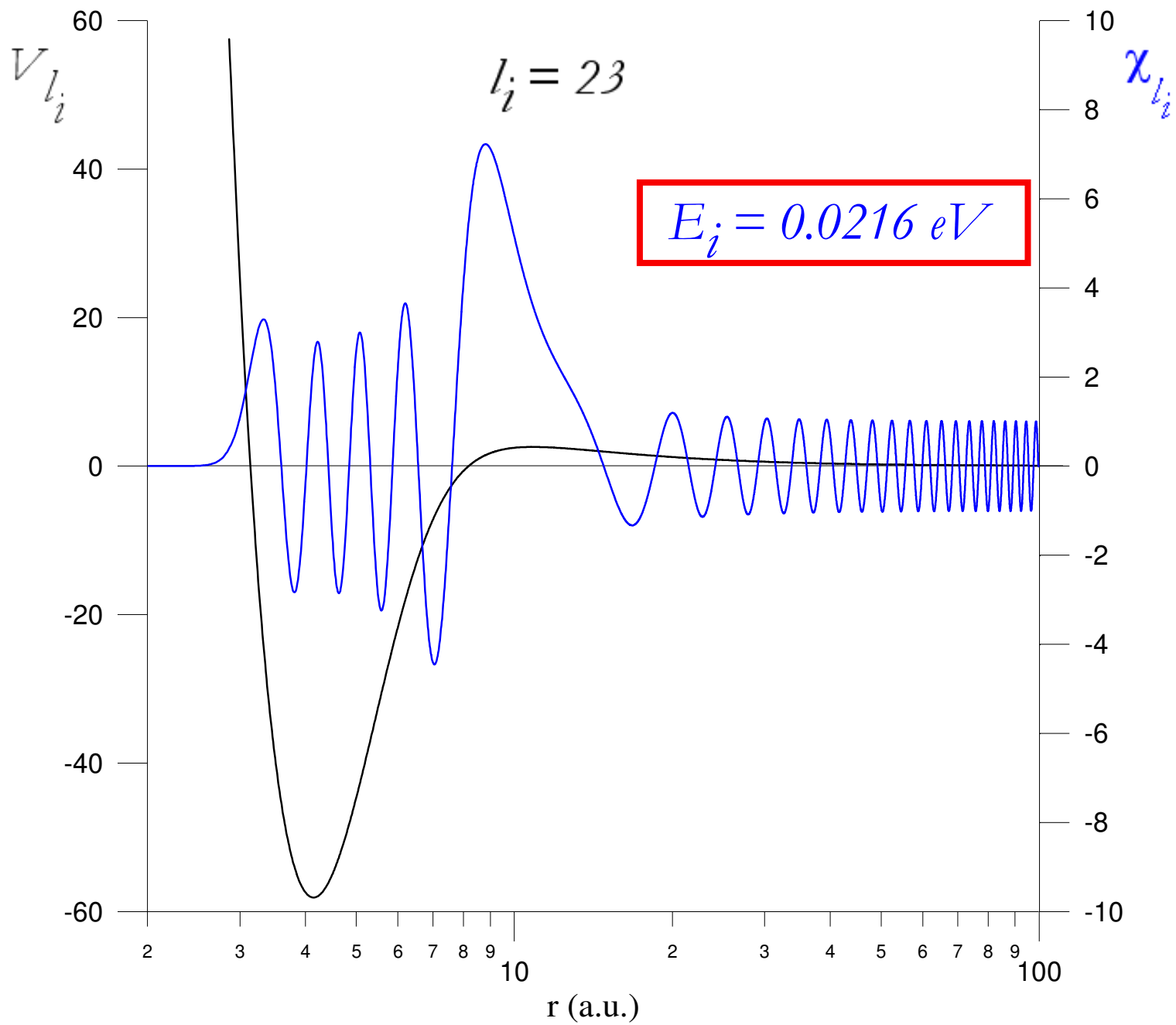


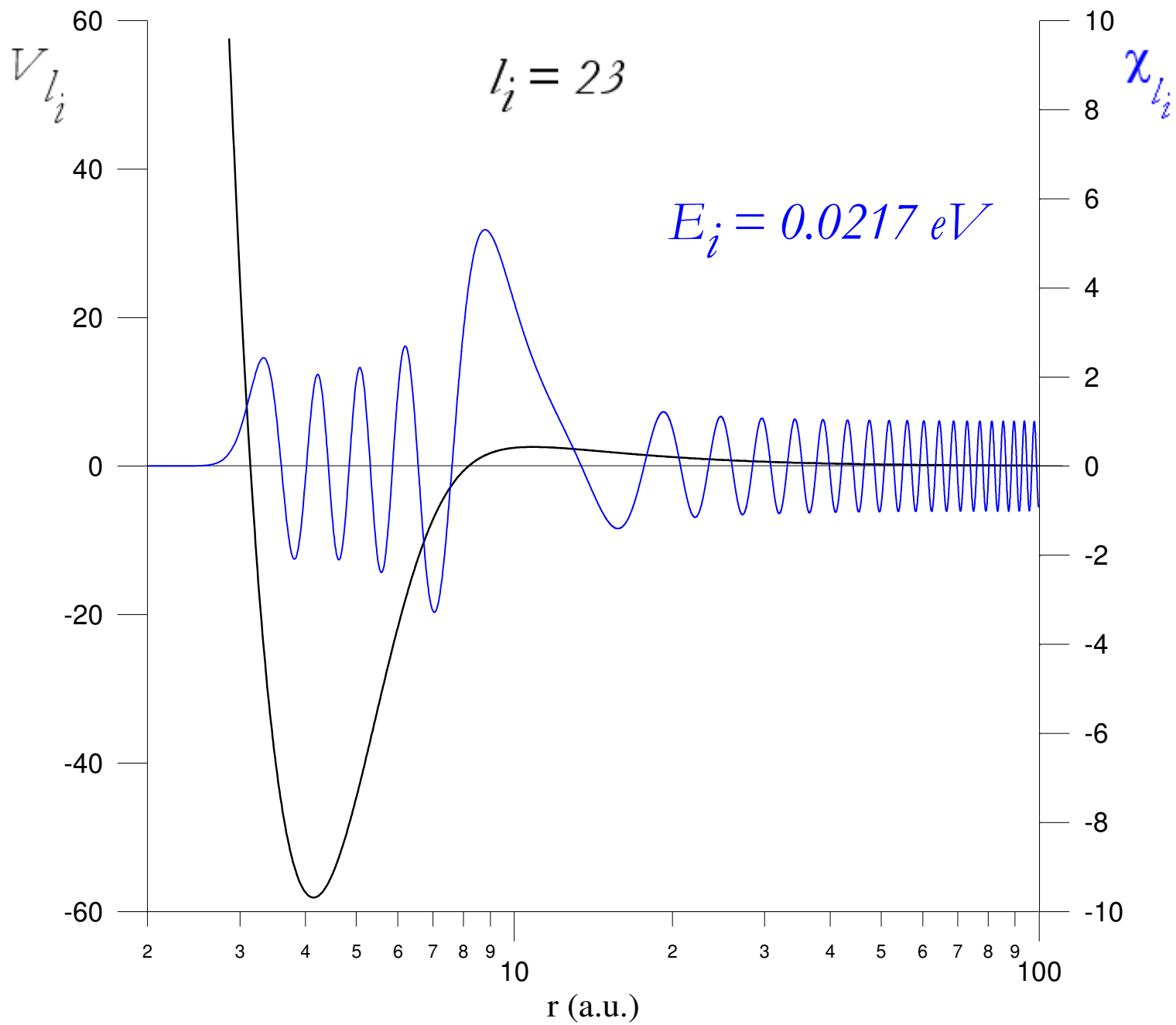


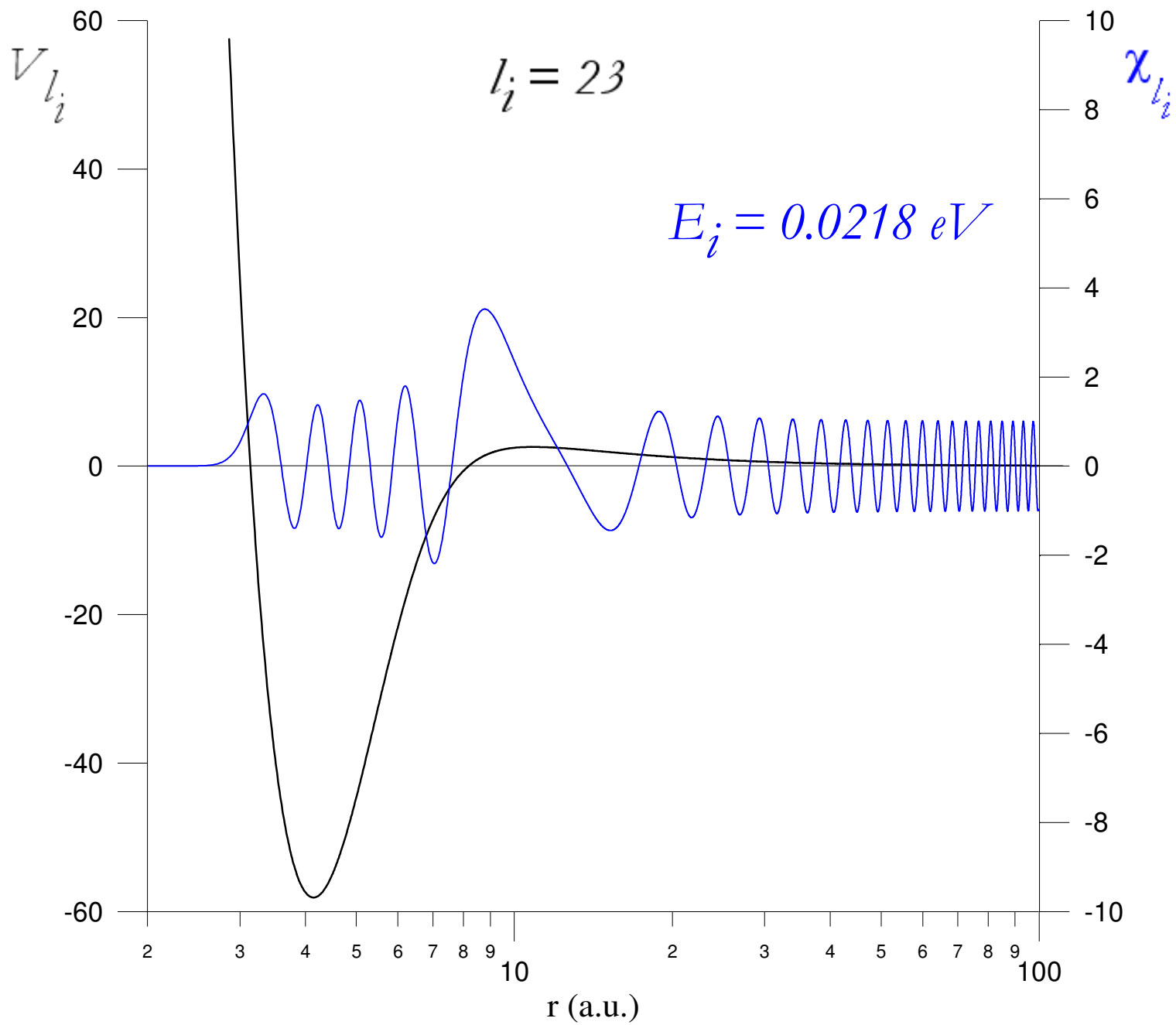


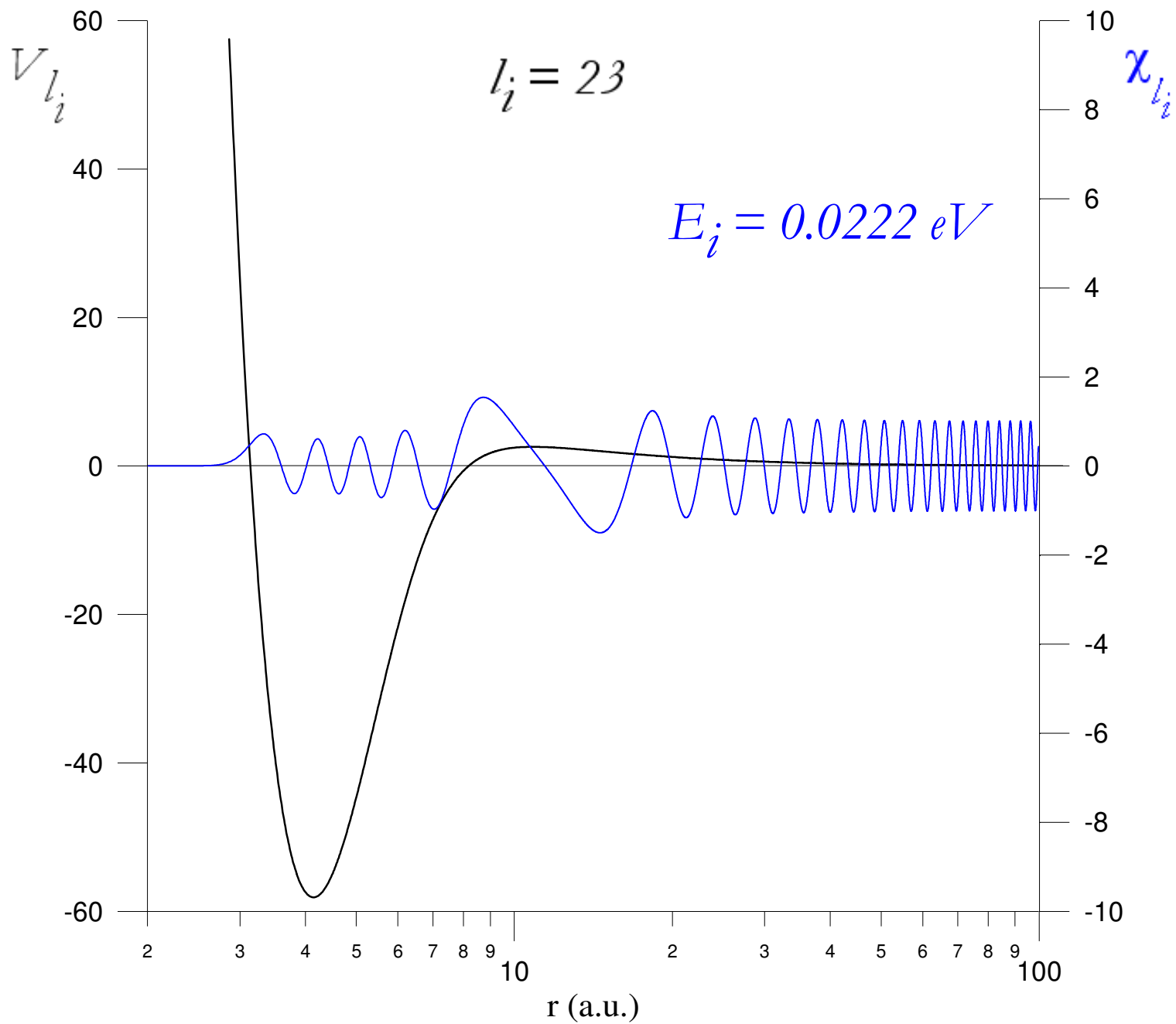


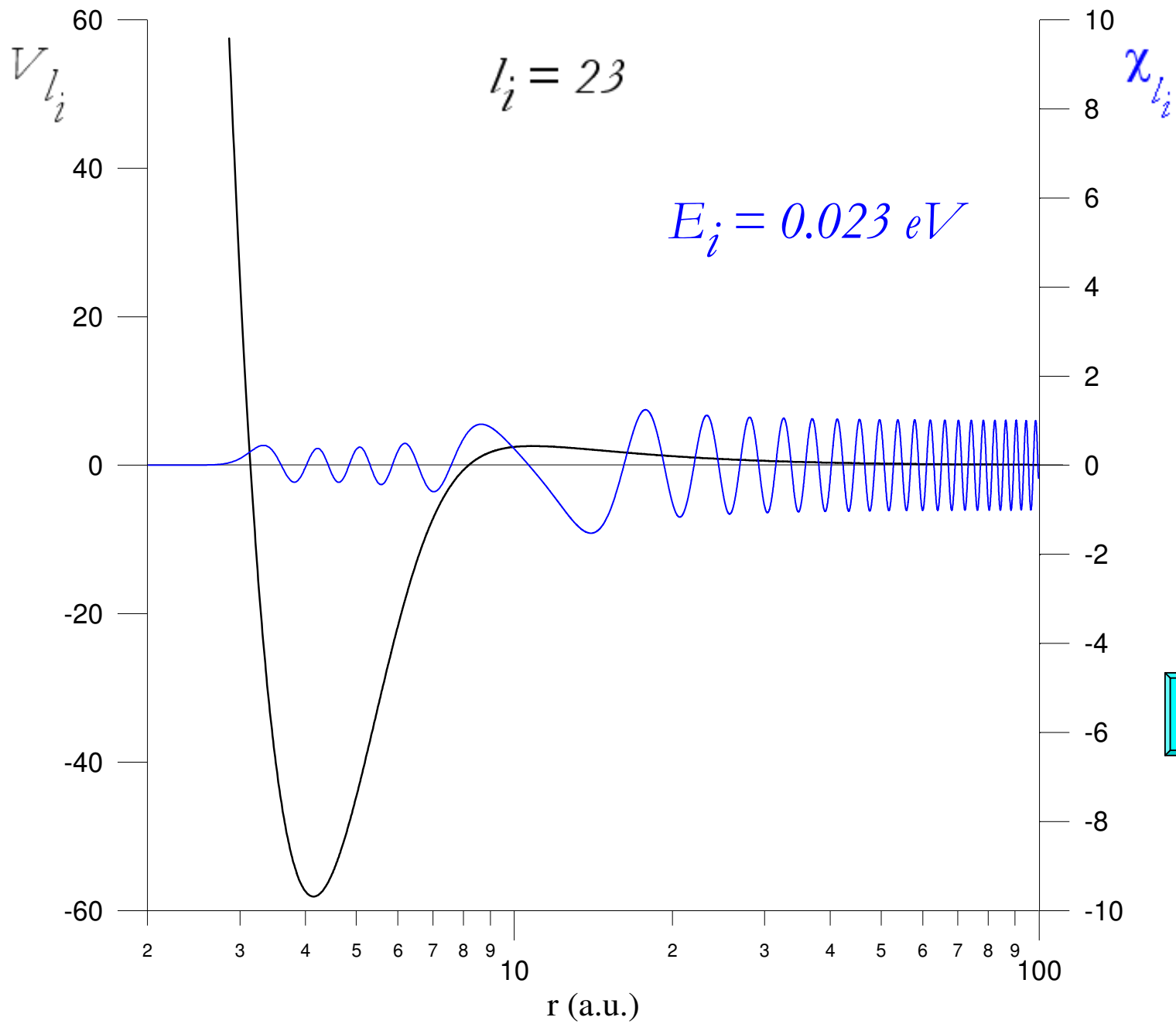


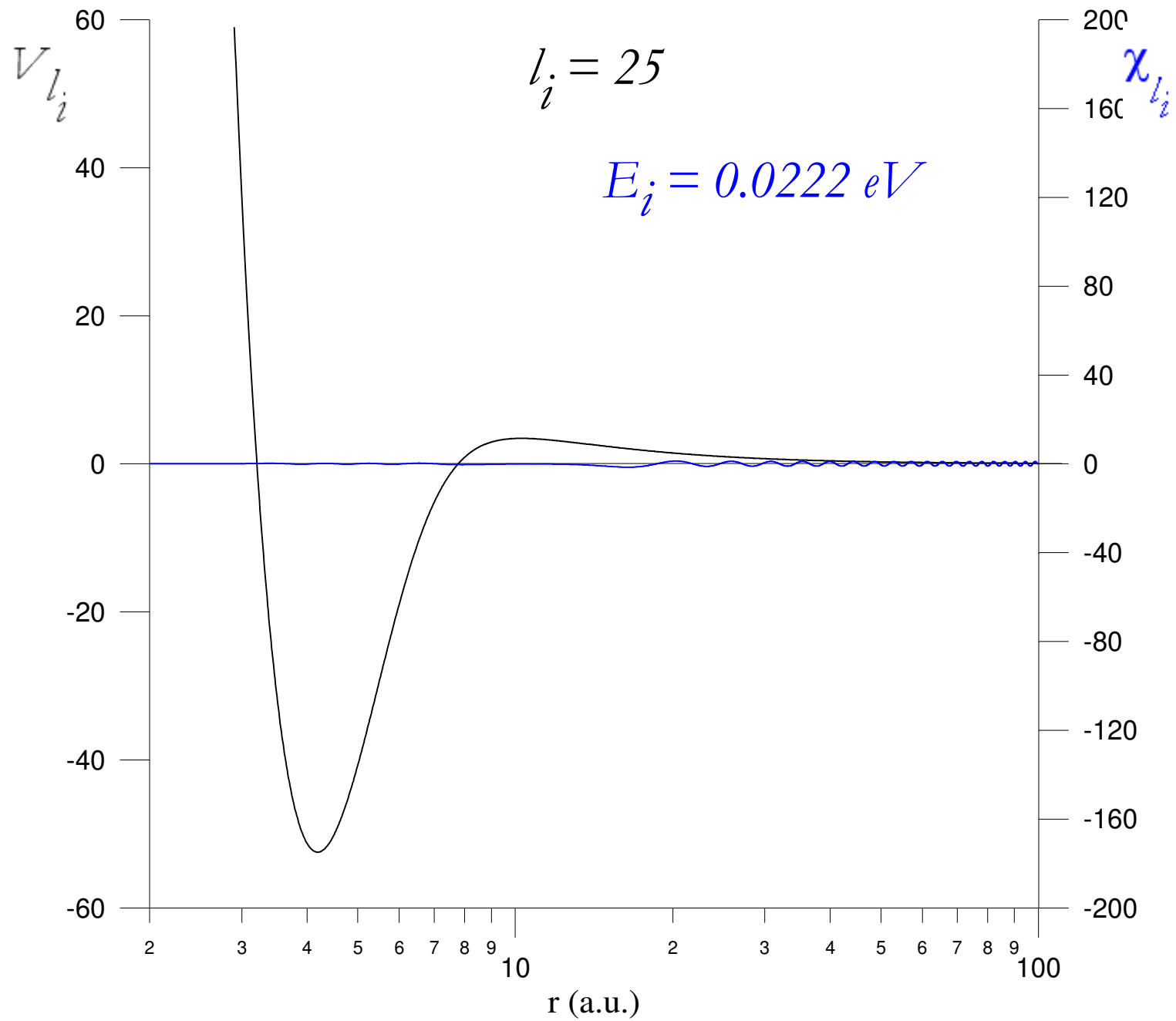


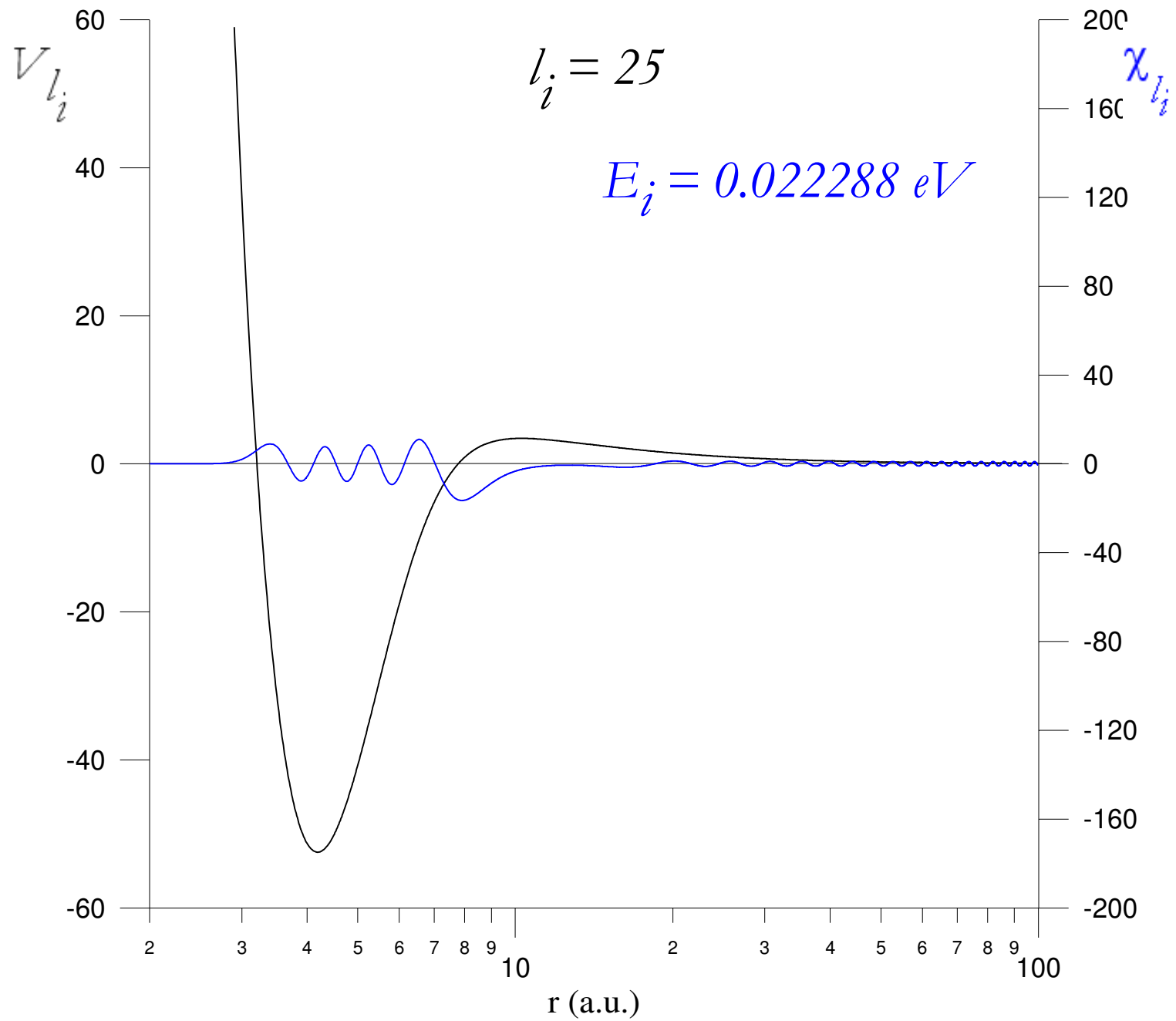


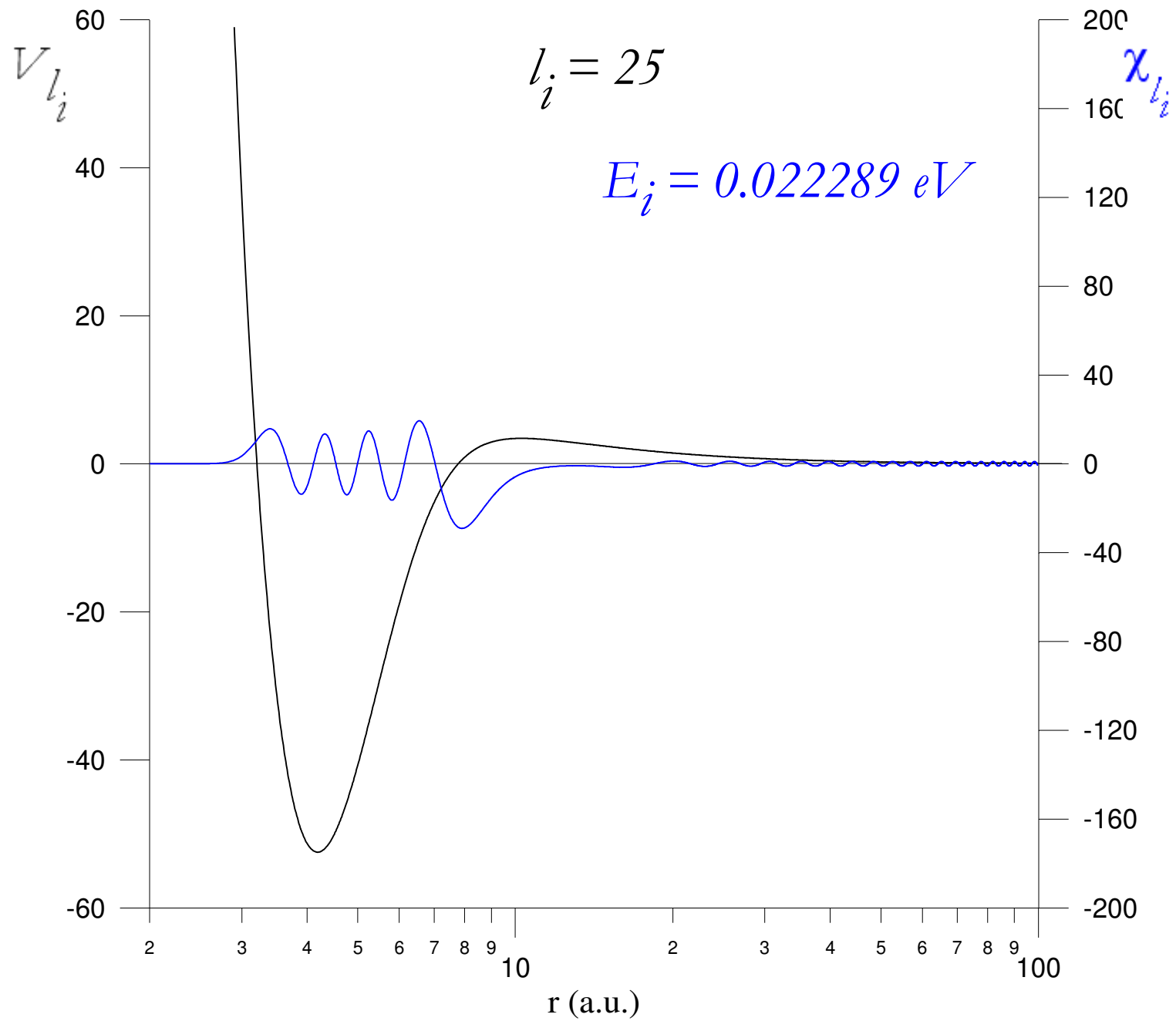


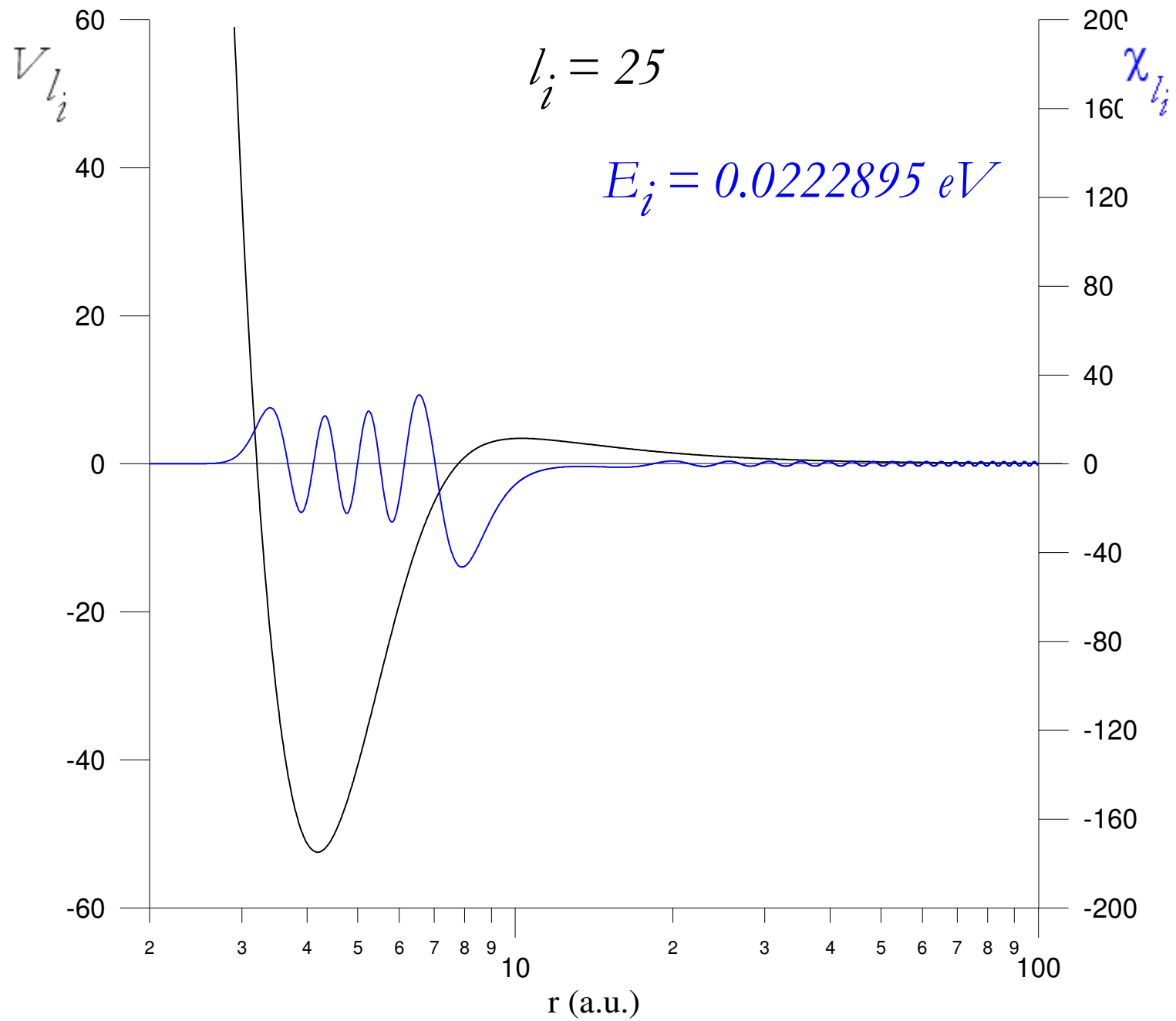


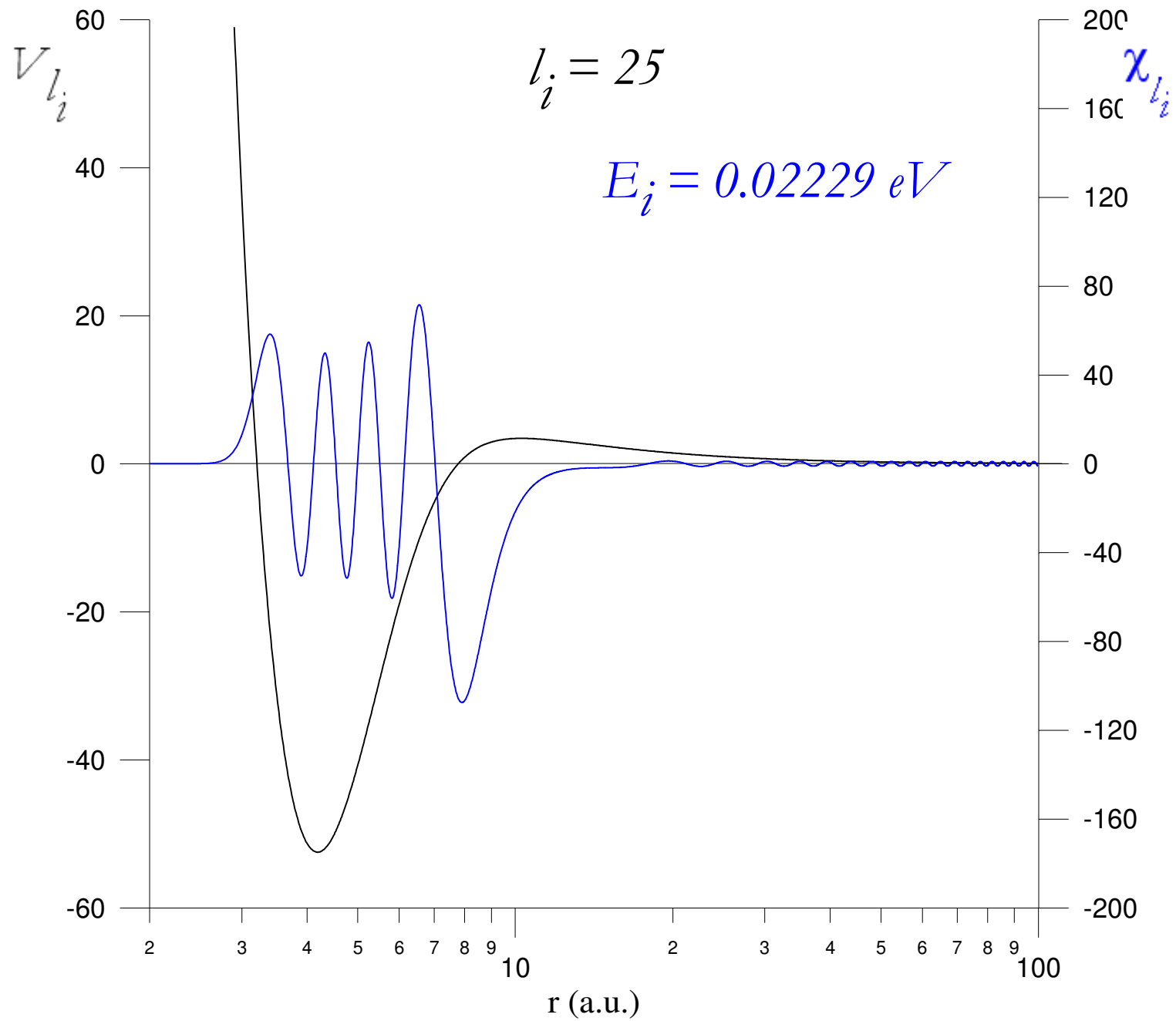


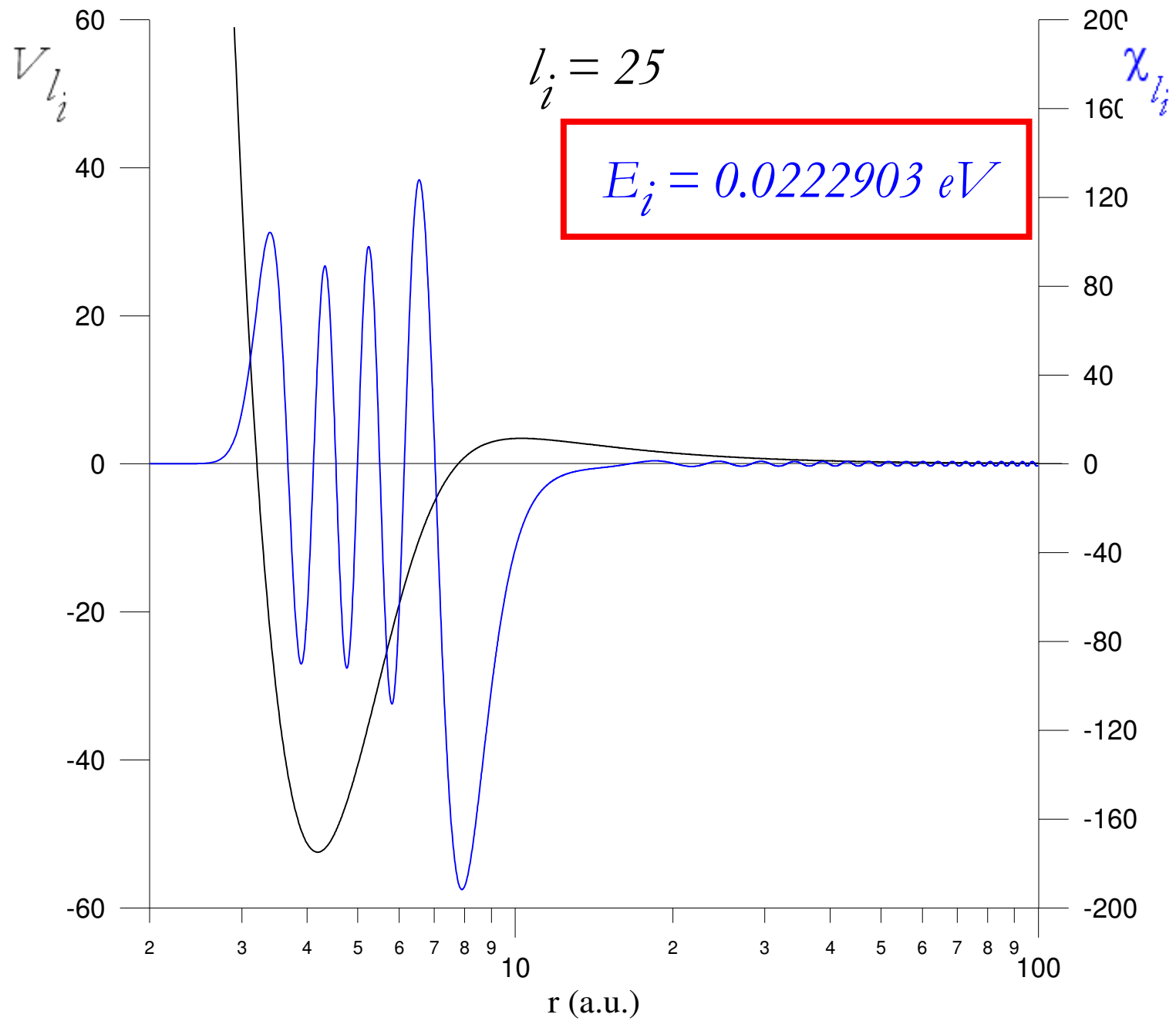


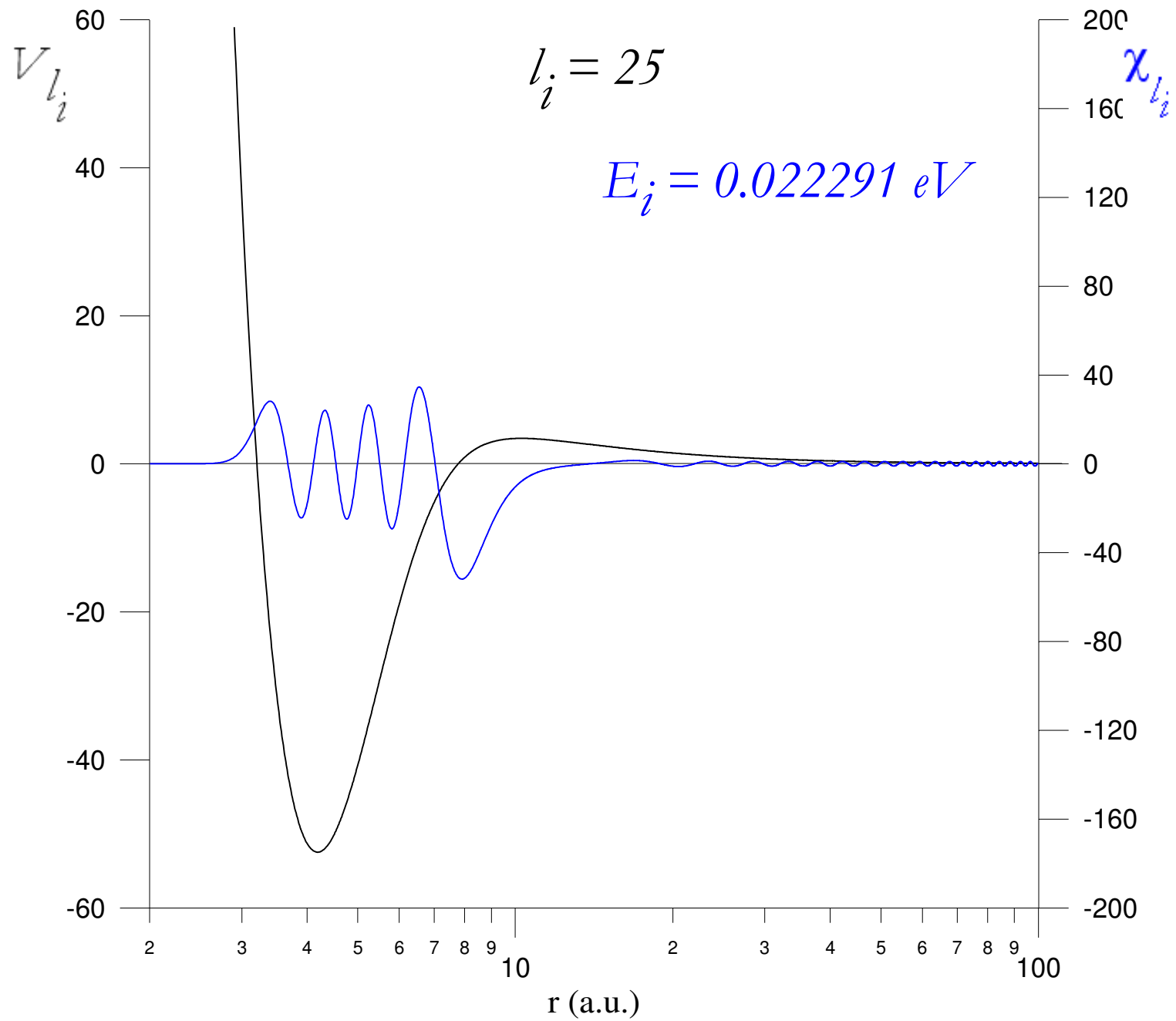


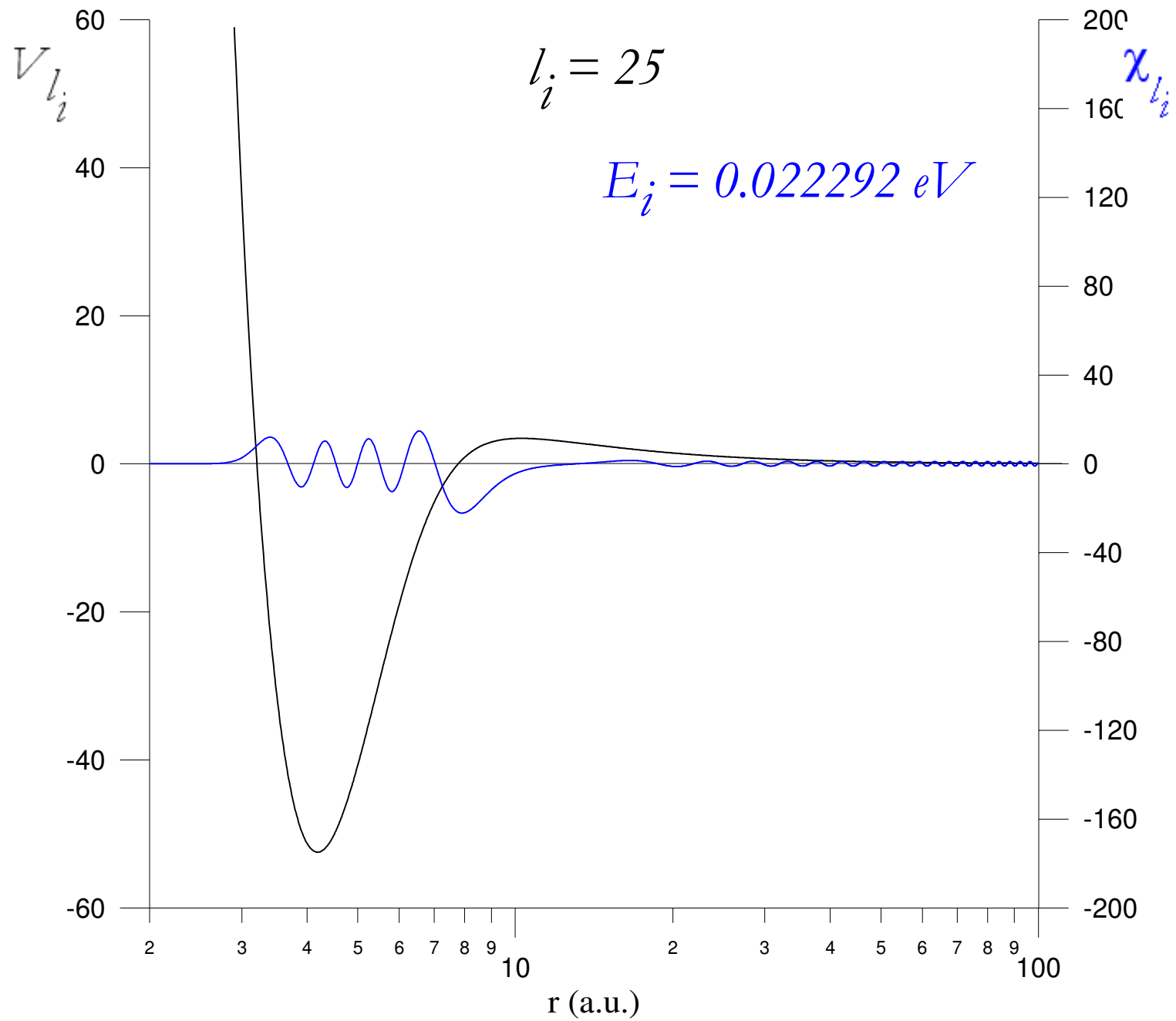


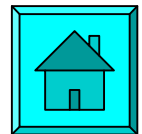
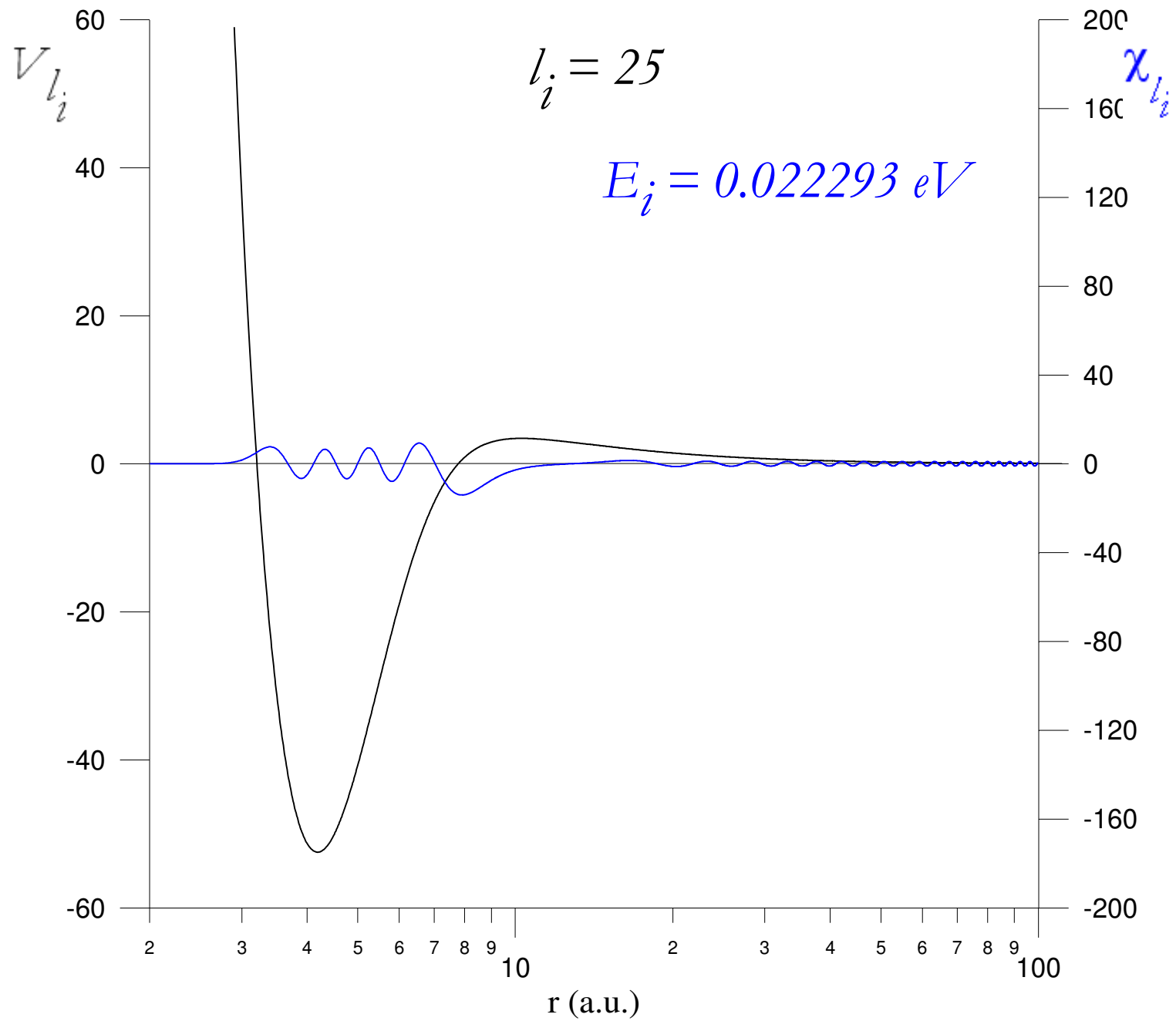






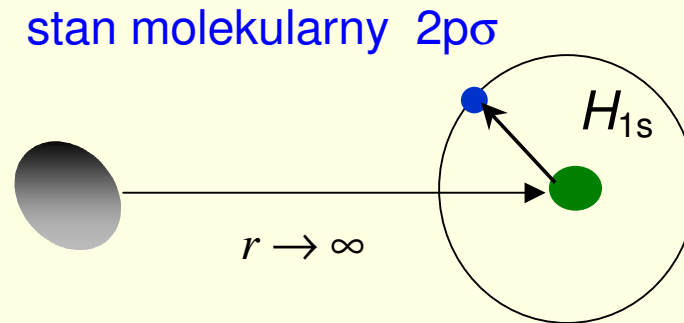
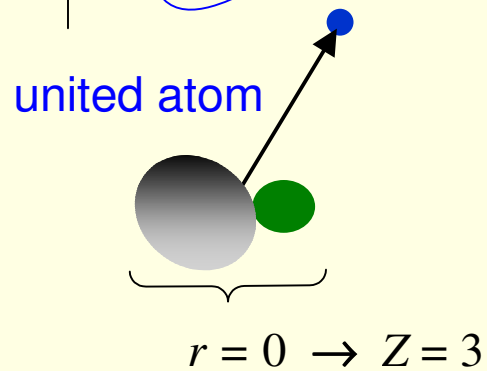
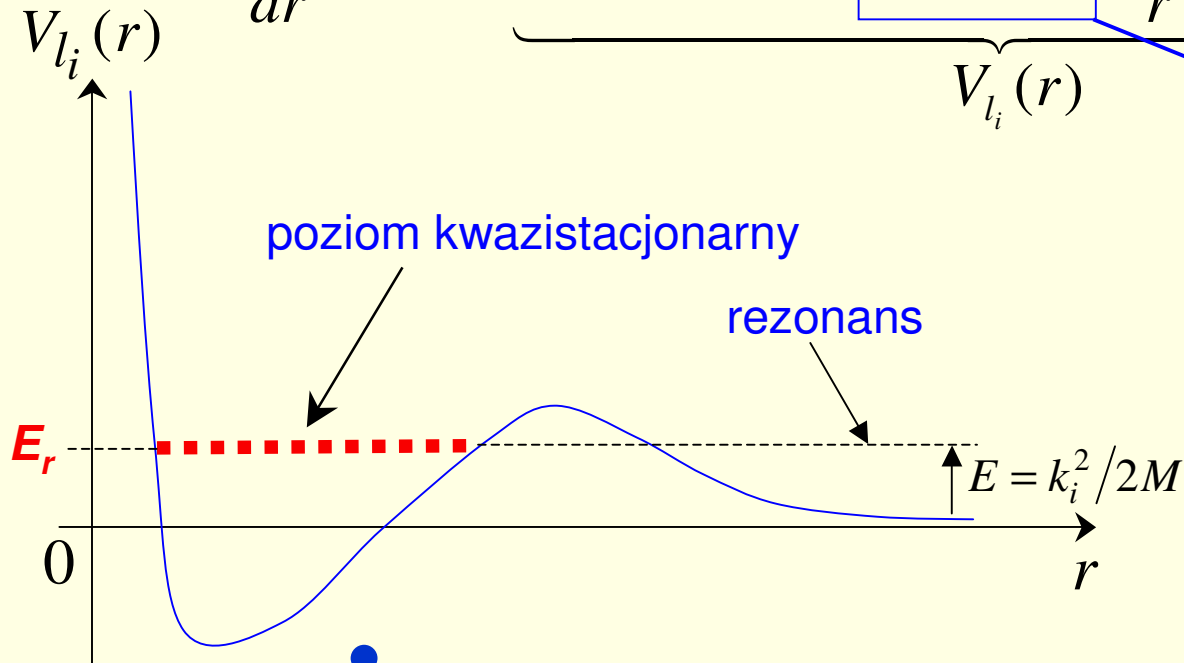




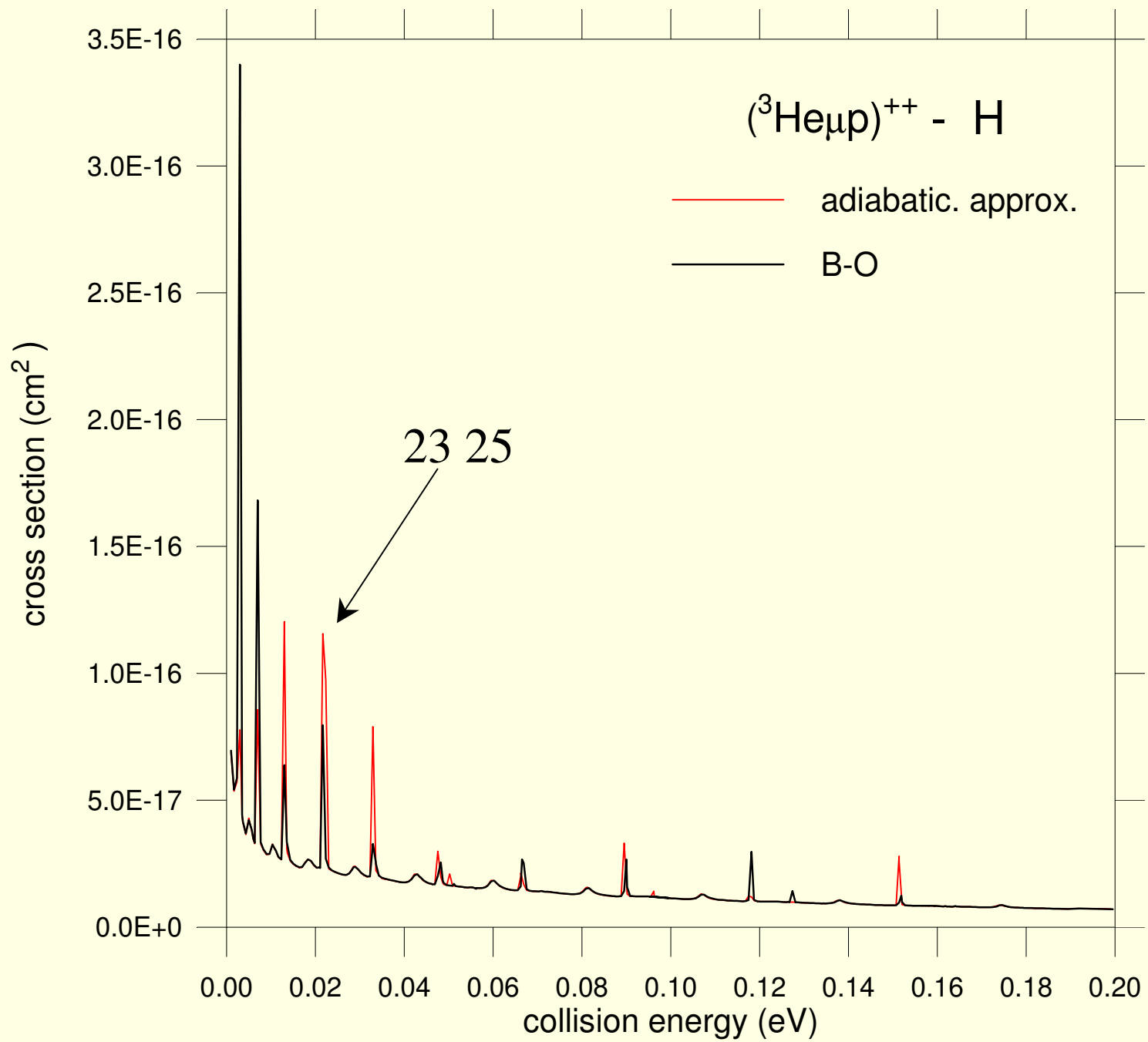


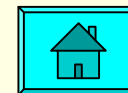
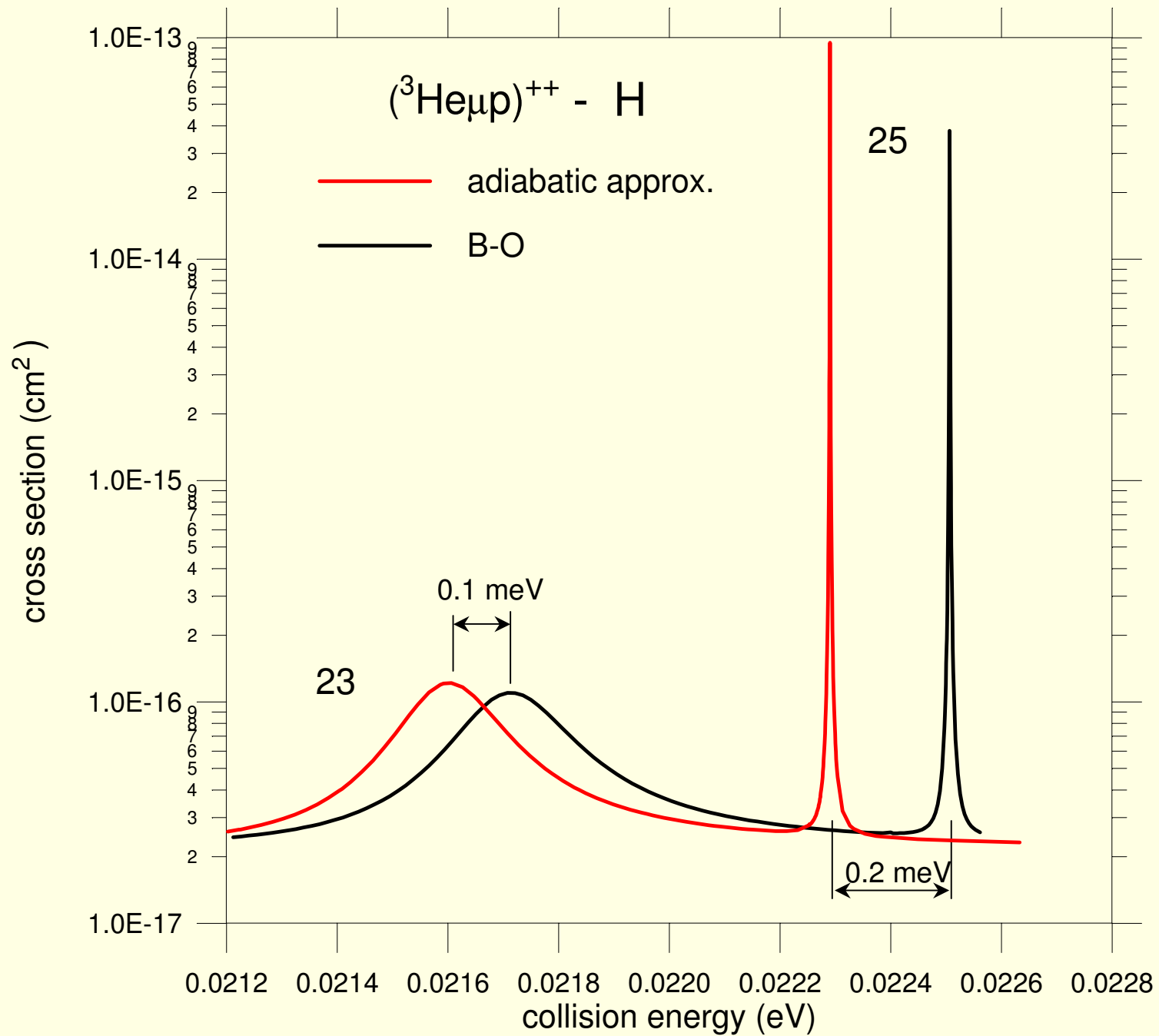
Przybliżenie adiabatyczne:

$$\left[\frac{d^2}{dr^2} + k_i^2 - \underbrace{2M(E_{2p\sigma}^e(r) + V_{ad.cor}(r) + \frac{2}{r^2}) - \frac{l_i(l_i+1)}{r^2}}_{V_{l_i}(r)} \right] \chi_{l_i}(r) = 0$$



sferyczne l. kwantowe elektronu $Nlm = (2,1,0) \equiv 2p\sigma$





Asymptotyka funkcji radialnej $\chi_l(r)$:

$$\left[\frac{d^2}{dr^2} + k^2 + V_l(r)\right]\chi_l(r) = 0$$

dla $r \rightarrow \infty$ $\left[\frac{d^2}{dr^2} + k^2\right]\chi_l(r) = 0$ - r. oscylatora

$$\chi_l(r) \sim \sin\left(kr - l\frac{\pi}{2} + \delta_l(E)\right) \quad E = k^2/2M$$

← przesunięcie fazowe

$$\sim e^{-i(kr - l\pi/2)} - e^{i(kr - l\pi/2)} \underbrace{e^{2i\delta_l}}_{S_l}$$

← element macierzowy macierzy rozpraszania

WKW istnienia rezonansu kształtu - RÓWNOWAŻNE

1. Amplituda fali $\gg 1$ w studni potencjału
2. W otoczeniu E_r , $\delta_l(E)$ zmienia się szybko o ok. π
3. Opóźnienie czasowe $\tau_l(E) = 2\frac{d\delta_l(E)}{dE}$ ma ostre maksimum w E_r

Opóźnienie czasowe: R - obszar oddziaływania (o.o.)

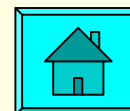
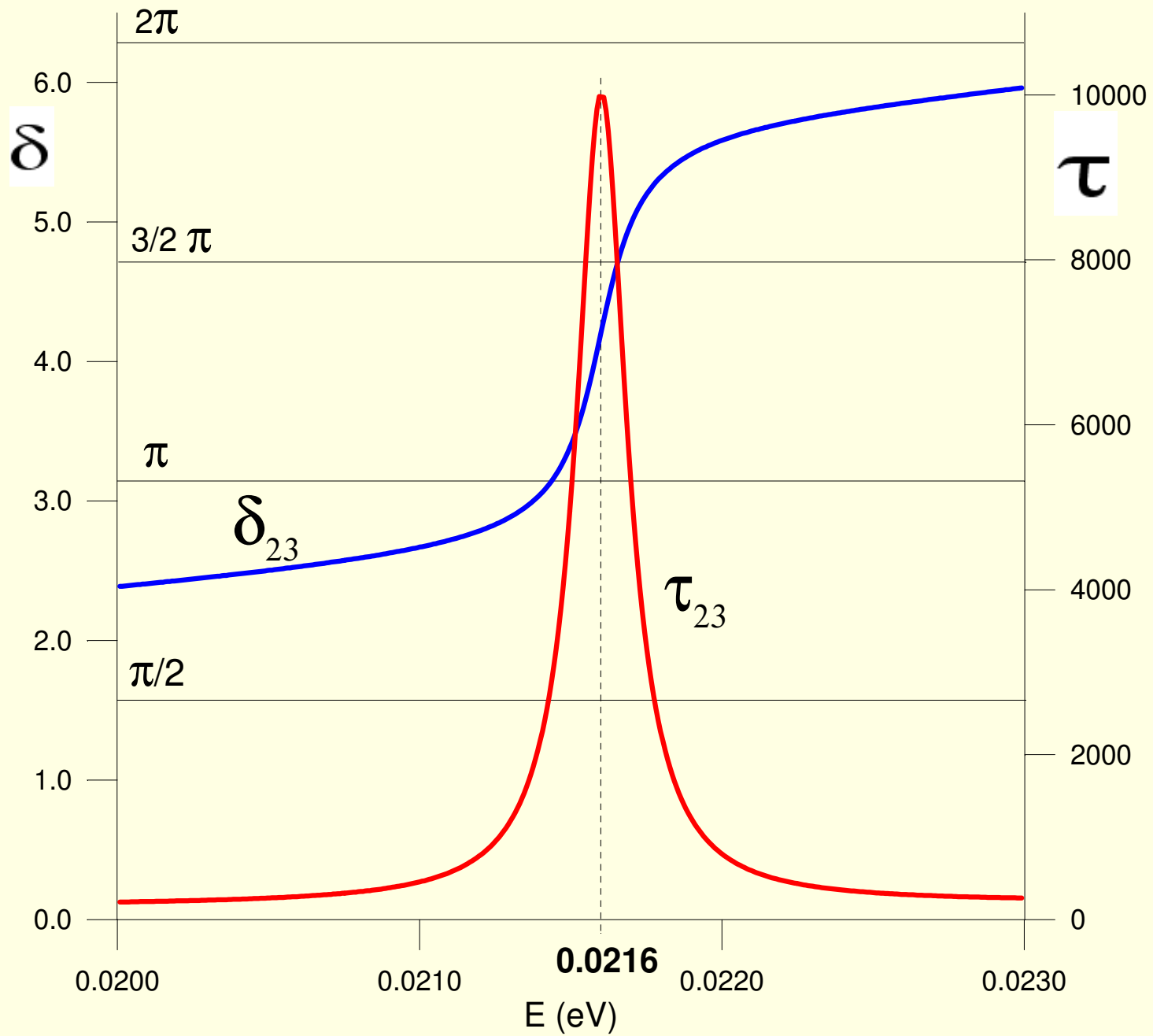
$$T(R) = \int_{-\infty}^{\infty} dt \int_{\frac{4}{3}\pi R^3} d^3 r |\Psi(\vec{r}, t)|^2 \quad - \text{czas przebywania w o.o.} \quad V(r) \neq 0$$

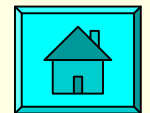
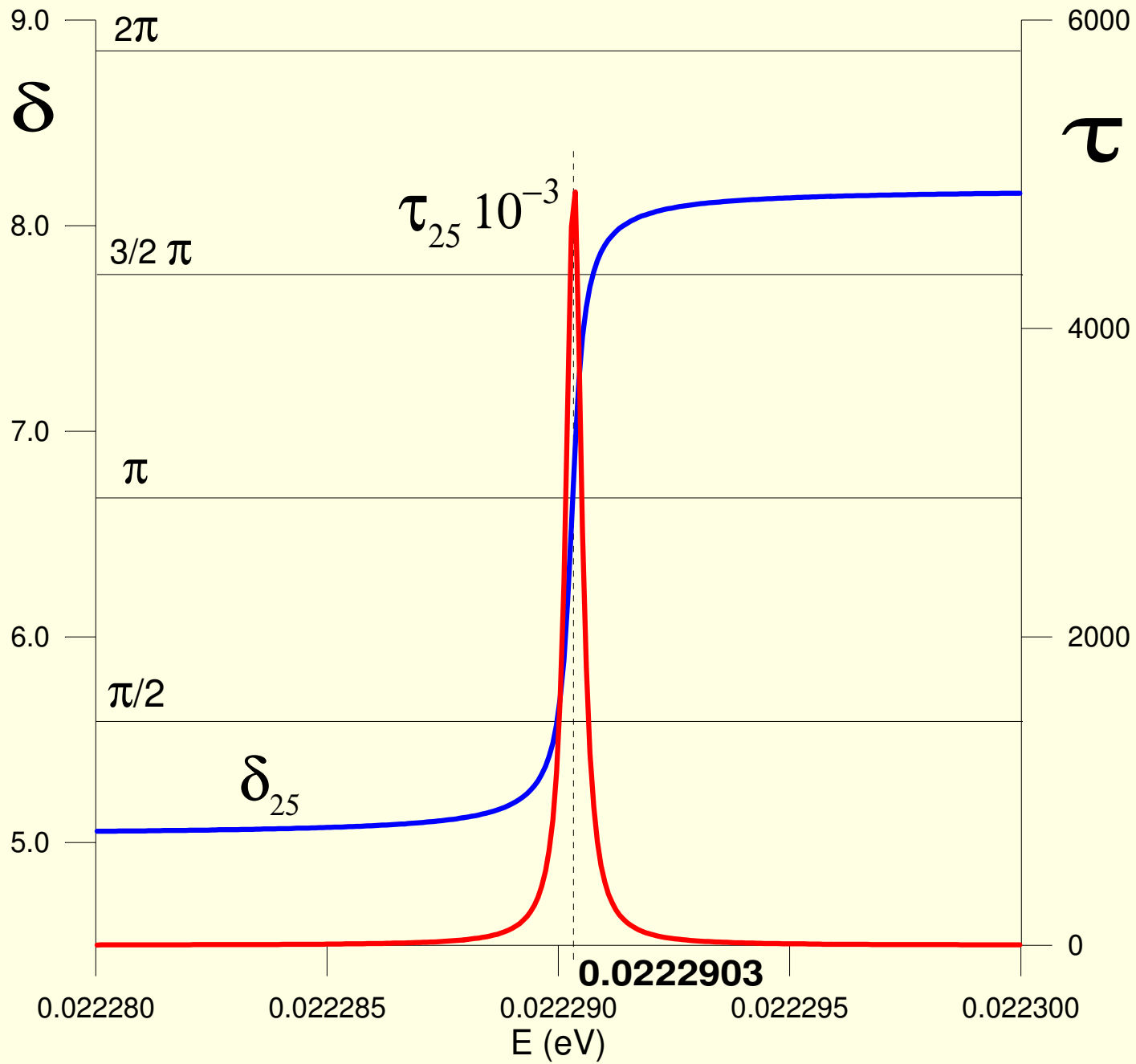
$$T_0(R) = \int_{-\infty}^{\infty} dt \int_{\frac{4}{3}\pi R^3} d^3 r |\Psi_0(\vec{r}, t)|^2 \quad - \text{czas przebywania w o.o.} \quad V(r) = 0$$

$$\begin{aligned} \tau(R) &= T(R) - T_0(R) = \int_{-\infty}^{\infty} dt \int_{\frac{4}{3}\pi R^3} d^3 r \left[|\Psi(\vec{r}, t)|^2 - |\Psi_0(\vec{r}, t)|^2 \right] = \\ &= - \int_{-\infty}^{\infty} dt \int_{\mathfrak{R}^3 - \frac{4}{3}\pi R^3} d^3 r \left[|\Psi(\vec{r}, t)|^2 - |\Psi_0(\vec{r}, t)|^2 \right] = \dots = \frac{1}{2} \sum_{l=0}^{\infty} \int_0^{\infty} dE |\Psi_0(E)|^2 \tau_l(E, R) \end{aligned}$$

po uśrednieniu po R : $\langle \tau(R) \rangle_R = \frac{1}{2} \sum_{l=0}^{\infty} \int_0^{\infty} dE |\Psi_0(E)|^2 \langle \tau_l(E, R) \rangle_R$

$$\langle \tau_l(E, R) \rangle_R = 2 \frac{d\delta_l(E)}{dE} \equiv \tau_l(E)$$





Czasy życia rezonansów:

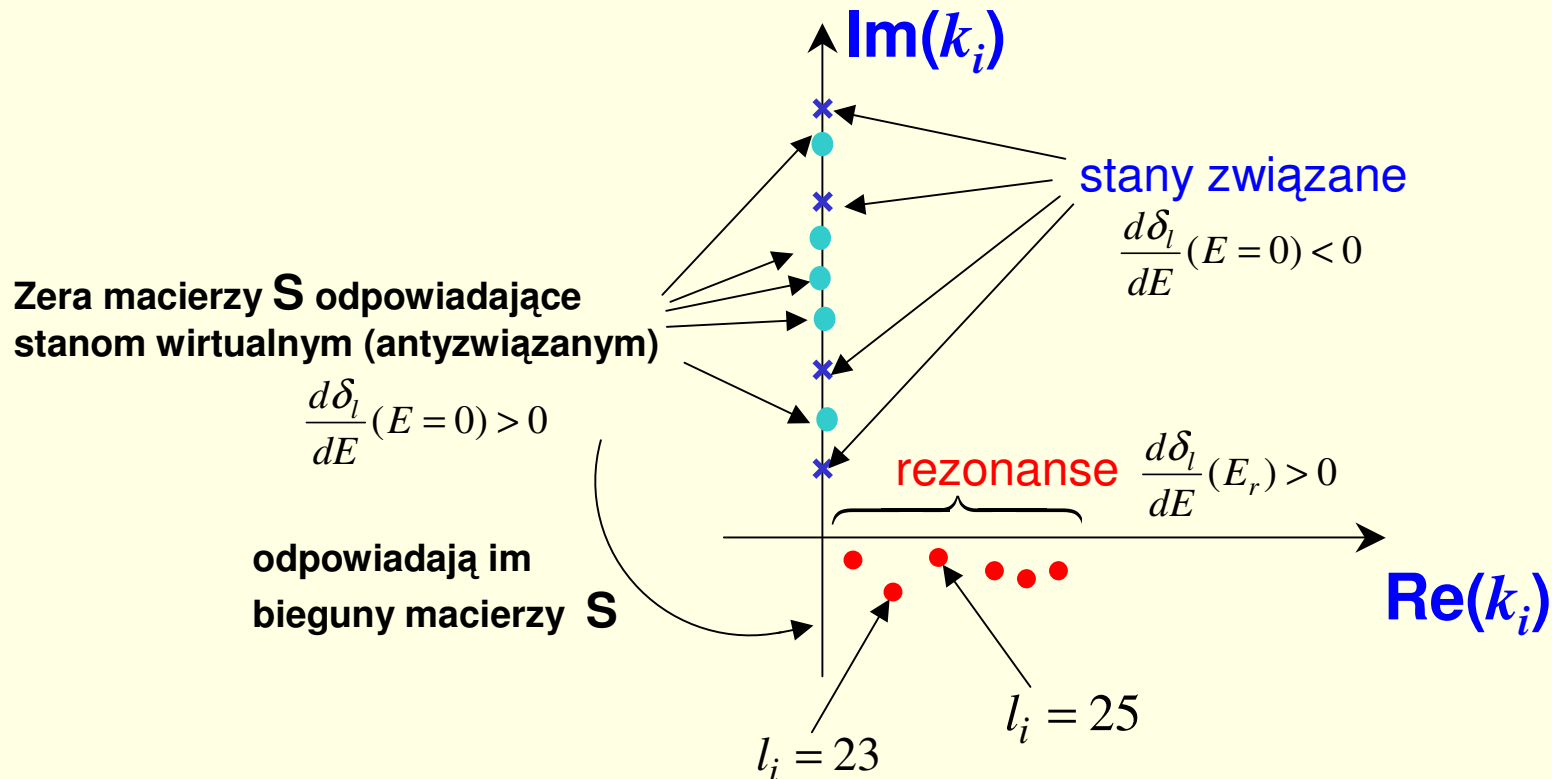
$$\sigma_l = \frac{4\pi}{k^2} (2l+1) \frac{(\Gamma_l/2)^2}{(E_{r,l} - E)^2 + (\Gamma_l/2)^2}$$



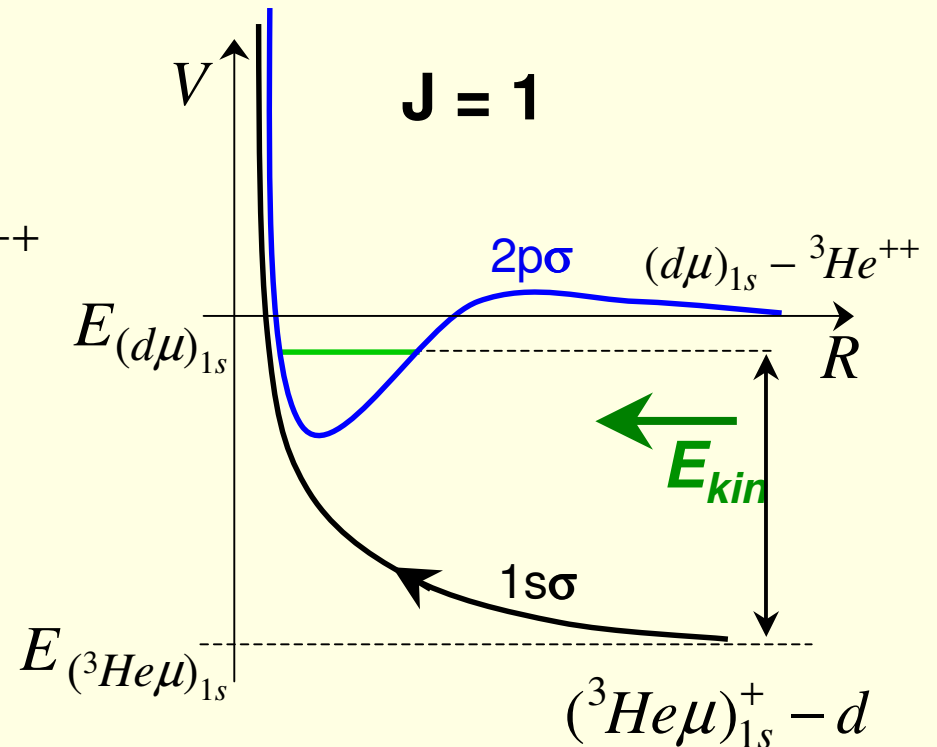
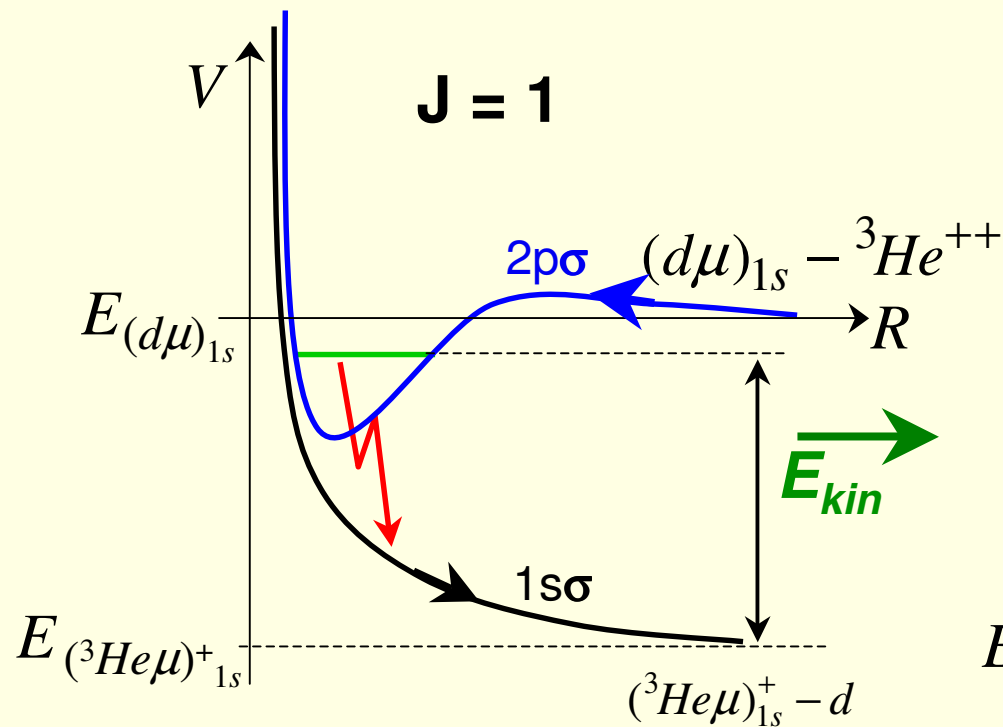
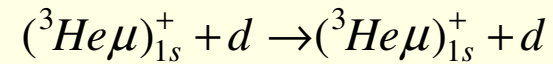
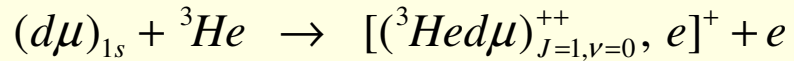
$$\Gamma_{23}^{-1} \approx 3.3 \cdot 10^{-12} \text{ s}$$

$$\Gamma_{25}^{-1} \approx 8 \cdot 10^{-9} \text{ s}$$

Płaszczyzna zespolonego wektora falowego \vec{k}_i - bieguny macierzy **S**



2. Rozpraszanie elastyczne atomów mionowych helu



Rezonans Feshbach'a

O.I. Kartavtsev, V.I. Kochkin and E.A. Kolganova

Joint Institute for Nuclear Research, Dubna 141980, Russia

Hyperfine Interactions 118 (1999) 235–237

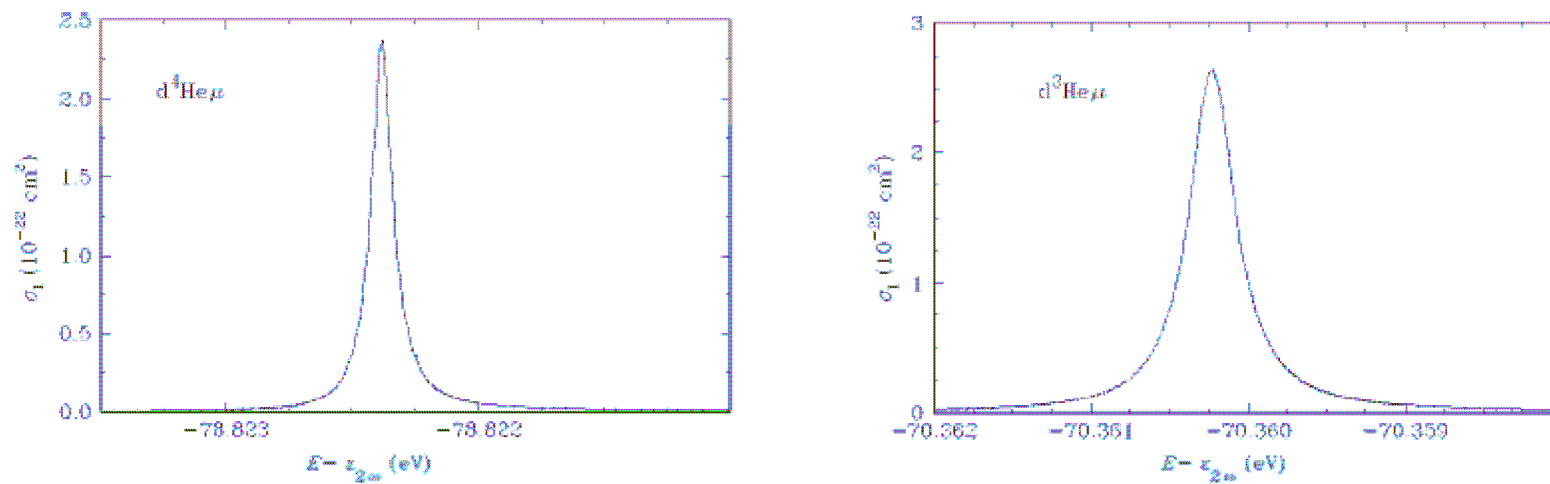


Figure 1. Elastic scattering cross-sections $^4\text{He}\mu + d$ (left) and $^3\text{He}\mu + d$ (right) in the vicinity of the molecular resonances.

Dziękuję za uwagę